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BINOCULAR RIVALRY IN HELMET-MOUNTED DISPLAY APPLICATIONS

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Hughes Aircraft Company

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DISPLAY SYSTEMS & HUMAN FACTORS DEPARTMENT
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA 90230

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A research program was conducted to determine the relationships between helmet-mounted display (HMD) design parameters and binocular rivalry. Four laboratory studies and a modulation transfer function image quality analysis were conducted during the course of the study program. A qualitative laboratory evaluation was conducted preparatory to the conduct of formal laboratory research to get a "feel" for the binocular rivalry phenomenon with HMDs prior to construction of laboratory equipment for formal research. A screening study which investigated 12 parameters was then

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conducted to determine which parameters affected binocular rivalry with HMDs. A parametric study was next conducted to establish functional relationships between HMD parameters and binocular rivalry for the parameters identified in the screening study to have a major impact on binocular rivalry. The final laboratory study was a validation study which compared selected HMD system configurations in realistic HMD and non-HMD tasks for binocular rivalry effects. The image quality analysis evaluated the effects of ambient illumination, display luminance, combiner transparency, and angular display subtense on HMD video image quality using modulation transfer function analysis techniques.

SUMMARY

Helmet-mounted displays provide a high quality, low cost, light weight display system that can be used in existing and new aircraft. Considerable effort has been expended in the last few years to develop such a display system. This development has resulted in several viable monocular designs that present a virtual image that is viewed by one eye, while the other eye is presented the ambient scene which may be the cockpit or the out-the-windscreen air or ground scene. The simultaneous presentation of different images to each eye can result in binocular rivalry. Binocular rivalry is an unstable condition during which either of the two images are alternately dominant or a montage of elements from the two disparate scenes is perceived. The occurrence of binocular rivalry can seriously degrade the task performance of the operator using a helmet-mounted display and limit operator acceptance of helmet-mounted display systems. This research program was conducted to determine the relationships between helmet-mounted display (HMD) design and binocular rivalry. To this end, four laboratory studies were conducted.

A qualitative laboratory evaluation was first conducted preparatory to formal quantitative research to obtain a preliminary assessment of binocular rivalry with HMDs. A Hughes monocular HMD demonstrator and auxiliary equipment to create the HMD image and ambient scene conditions were used. Observer comments were elicited under different HMD conditions, observer tasks, and ambient scene conditions. The qualitative evaluation revealed binocular rivalry to be a potential problem for extracting information from an HMD. Relative luminance of the HMD and non-HMD scenes, eye dominance, and relative scene complexity were observed to effect binocular rivalry. Percent see-through of the HMD and the presentation of a moving scene in the HMD had negligible effects on the occurrence of binocular rivalry.

A 2^{12} fractional factorial screening study was conducted after the qualitative evaluation to determine which of a large number of HMD design related parameters had major effects on binocular rivalry. The parameters were HMD resolution, visual subtense of the HMD, HMD luminance, ambient scene luminance, HMD percent transparency, HMD framing (side-mounted and visor projected HMDs), color, HMD accommodation distance, ambient scene accommodation distance, HMD eye presentation (eye dominance), HMD target contrast, and ambient scene complexity. An HMD simulator which used optical projection techniques was constructed to study these parameters. A mechanized quantified judgment task was used to measure the occurrence of binocular rivalry. Ambient scene complexity, HMD resolution, HMD luminance, ambient scene luminance, HMD accommodation distance, HMD field of view, and HMD contrast were found to have significant effects on binocular rivalry. Percent transparency, color, framing, eye dominance, and ambient scene accommodation distance did not affect binocular rivalry.

Based on the results of the screening study, a parametric study which investigated HMD resolution, HMD luminance, ambient scene luminance, HMD contrast, and HMD field of view each at three levels was conducted. The equipment and task were the same as used in the screening study. HMD and ambient scene luminance had the largest effects on binocular rivalry, accounting for 58 percent of the study variance. HMD contrast was found to affect rivalry at a low contrast. HMD resolution and field of view had negligible effects on binocular rivalry.

The fourth laboratory study was a validation study which compared selected HMD system configurations, derived from the results of the screening and parametric studies, in realistic HMD and ambient scene tasks for binocular rivalry effects. The laboratory equipment used in the screening and parametric studies was modified to present tactical target scenes on the HMD and a tracking task for the ambient scene. Target recognition time and tracking error were measured. Three HMD system configurations and two ambient scene luminance conditions were evaluated. The results were as predicted from the findings of the screening and parametric studies, verifying the applicability of the parametric research on binocular rivalry to HMD design. The implications of the findings of the four laboratory studies for the design and use of helmet-mounted displays are discussed in the report.

In addition to the laboratory research on binocular rivalry in helmet-mounted displays, an image quality analysis which evaluated the effects of HMD luminance, combiner transmittance, HMD field of view, and ambient illumination was performed. Modulation transfer function analysis techniques were used for this analysis. The visual cutoff frequency, the modulation at the cutoff frequency, the number of square root of two gray shades, and the modulation transfer function area were used to assess the effects of the parameters evaluated. Graphical and tabular data are given in the report which show the results of the analysis.

PREFACE

The research covered herein was initiated by the Aerospace Medical Research Laboratory, Air Force Systems Command, United States Air Force, Wright-Patterson AFB, Ohio, to investigate helmet-mounted display design parameters and binocular rivalry. The contract was initiated under Air Force Project 7184. The Technical Monitor for the Air Force was Mr. H. Lee Task (6570 AMRL/HEA). The research was conducted by the Display Systems and Human Factors Department of Hughes Aircraft Company, Culver City, California, under USAF contract F33615-73-C-4145. Mr. M.L. Hershberger of Hughes Aircraft Company was Project Manager.

Special acknowledgment is gratefully made of the following contributions to the performance of the research. Mr. H. Lee Task of AMRL provided valuable technical guidance during the course of the research effort. Dr. C.W. Simon, of Hughes Aircraft Company, conducted the Qualitative Evaluation of Binocular Rivalry Effects on Helmet-Mounted Displays. Mr. W.H. Smith, of Hughes Aircraft Company, performed the Image Quality Analysis which was part of the research effort. Mr. R.E. Heineman, of Hughes Aircraft Company, designed and constructed the laboratory equipment which was used in the quantitative laboratory research investigations.

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SECTION 1

INTRODUCTION AND BACKGROUND

The advantages of cost, weight, ease of installation, and operational utility of virtual image helmet-mounted displays (HMD) have accelerated the funding of the development of these devices during the past few years. Most of the effort has been directed towards solving the engineering problems of designing a high quality helmet-display that may be worn and viewed comfortably by the pilot. There are, however, some perceptual problems associated with HMDs that must be solved by proper design if HMDs are to realize the operational potential expected of them.

Unlike conventional displays, the virtual image from a helmet-mounted display will characteristically be viewed by one eye, while another image, the ambient scene, will be presented to the other eye. In this class of devices, the image source, typically a cathode ray tube, is not viewed directly but through a series of optics and a combining glass. The combining glass itself may be opaque to the external ambient or have some percentage of transparency. With a partially transparent combining glass, the cockpit or the local terrain may also be visible to the HMD eye. The simultaneous presentation of different images to each eye of an observer can result in binocular or retinal rivalry which consists of an unstable condition where either of the two images are alternately dominant or what is perceived is a montage of elements from the disparate scenes. Rivalry may also result in severe eye fatigue and headaches. Flight test studies conducted at Hughes Aircraft Company (Jacobs, Triggs, and Aldrich, 1970) suggest that pilot acceptance of HMDs will not be universal unless the problem of rivalry is avoided in HMD design and use.

The design of the HMD to satisfy the requirements for control of binocular rivalry may involve design characteristics that sacrifice image quality and thereby the utility of the display as a media for target recognition. It is important therefore that the impact of HMD design characteristics on the incidence of binocular rivalry and image quality be well understood. The research reported herein was directed at determining the relationships between HMD design parameters and binocular rivalry.

BACKGROUND

Binocular rivalry is a phenomenon that occurs when different images are simultaneously presented to each eye in such a way that binocular fusion of the two images cannot occur. The phenomenon is manifested either by the two images alternating as the dominant one, or an unstable montage is formed comprised of elements from each field. The alternation rate during rivalry is not under complete voluntary control of the observer.

Rivalry is obviated when one of the two images so completely dominates the other that alternation of the two fields does not occur. This is a desirable situation from the point of view of HMD design if the conditions

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under which one or the other field will dominate can be identified and placed under the control of the observer. Essentially, this was one of the primary goals of the study.

Several theories exist that attempt to account for the phenomenon of rivalry. Helmholtz in 1886 suggested an attention theory where he considered that competition took place in central processes. There are two perceptions, and attention determines which one will come to awareness. This theory tends to be circular, as what determines attention can only be empirically determined. An alternative theory is that of Hering in 1864 who considered that the binocular impression arises from a mixture of monocular excitations, where the excitations from corresponding areas are not summative. In other words, each retina makes a contribution, but the amount depends on the nature of the image. In Hering's view, contours always dominate, and this is the hard core of his rivalry explanation. This theory does not depend on experimental factors or the mental set of the observer. Another theory, based on the Gestalt school, suggested that the important factor was that a figure is either perceived entirely or not at all, and that this requirement leads to competition.

More recently, Levelt (1965) has discussed these theories in detail and has presented an alternative theory which considers that rivalry is a result of conflict between two visual mechanisms, namely binocular brightness averaging, which operates so as to average out the brightness for corresponding points of the two eyes, and a contour mechanism which acts so as to leave the area in the vicinity of a distinct contour unimpaired.

One property of the binocular rivalry situation is that the operator's reaction time to a critical signal in the suppressed eye will be slowed (Fox and Check, 1968). This reduced responsiveness of the suppressed eye is further demonstrated by the fact that no pupillary reflex is found when an inhibited eye is stimulated by a flash during binocular rivalry (Bokander, 1967).

A large body of basic laboratory research literature exists concerning binocular rivalry. A review of this literature was made. From this review, a set of factors that affect binocular rivalry was identified. These factors are discussed in the following paragraphs in the context of related HMD design variables. The bibliography comprising the review of the literature is presented in Appendix A of this report. A more recent literature review of psychological considerations in the design of HMDs can be found in Hughes, Chasen, and Schwank (1973).

LUMINANCE RATIO

The field with the greater luminance will tend to dominate. This means that the luminance ratio between the external scene and the scene presented on the display is critical. On a bright day (>2000 fL), the external scene will, by this rule, dominate if the display is orders of magnitude dimmer. For the observer to obtain a clear, dominant display image, he must increase the brightness of the display and/or decrease the amount of light from the external scene. It is not known whether the controlling factor is the constant luminance ratio between the competing images or the absolute difference in luminance between the two scenes that causes rivalry.

It is clear that if the HMD scene is to be dominant over the outside scene, it must be brighter. The state of the art in HMD design is currently limited to a peak luminance of approximately 400 fL, as transmitted through the optics to the eye. Even if 1000 fL were available, it is unlikely that the HMD scene would dominate in a high ambient environment. Further, running the CRT brightness up so high may cause the CRT beam spot to bloom thus reducing resolution. It is possible to reduce the luminance to the eye viewing the outside scene to make the eye receiving the HMD image dominant, but this may be operationally unacceptable. Conversely, the brightness of the CRT may have to be reduced under night conditions, since it may be too intense for perception of the immediate surroundings.

PERCENT TRANSPARENCY

Percent transparency is a factor which could affect the degree of binocular rivalry that will be experienced. Percent transparency refers to the amount of light from the external scene that is passed through the combiner to the observer's eye. The display can be designed to be fully occluded (no external light passes through to the eye) or virtually unoccluded where almost all of the ambient scene illuminance reaches the HMD eye. Through a choice of filters, virtually all degrees of transparency from 0 to 100 percent can be obtained. Even a low degree of transparency may cause the display to become washed out due to external illumination. With a fully occluded display, the effects of external illumination on the HMD eye are eliminated.

In the Hughes flight test studies, it was found that the degree of binocular rivalry was reduced when a partially occluded eyepiece was employed so that the eye receiving the CRT information could also see through the display to view the outside scene. However, providing a see-through capability, while helping the rivalry problem, can result in reduced image quality. Section 4.0 of this report shows that even for a combiner filter that transmits as little as 1 percent of the outside light, the MTF of the display, dynamic range, and number of shades of gray are significantly reduced for ambient intensities of typical sunlit days.

CONTRAST

Levelt (1965) attributed the dominance and frequency features of the alternation process in binocular rivalry to a variable called "stimulus strength". The stimulus strength of a field was assumed to increase with amount of contour per area and, for a constant amount, with the strength of these contours. Contour strength may be increased by increasing the physical contrast of a test field. Predominance of the HMD field should vary directly with changes in HMD image contrast and inversely with contrast variations in the contralateral field image.

IMAGE RESOLUTION

Given one clear field and one blurred field, the clear will tend to dominate. This factor is related to the resolution of the HMD. Alternation between the two fields is a function of the relative difference in image sharpness. The extent to which the HMD image must be sharp in terms of display resolution when compared to the outside scene as seen by the other eye is unknown.

It is possible that image resolution interacts with display luminance to affect binocular rivalry. The rivalry literature states that image quality factors such as image sharpness, contrast, and number of contours (amount of detail) all help determine which scene will be dominant. Image sharpness and number of contours are related to the resolution of the HMD system.

COLOR

In most situations, the spectral content of the HMD image and the external scene will differ considerably. To a great extent, the respective color compositions of these two visual fields may be manipulated by the design of the HMD. The external visual scene color content may be transmitted to the viewing eye unchanged, or may be adjusted by passage through an interposed chromatic filter. The color characteristics of the CRT image will depend upon the phosphor type selected. A multiple-color HMD may be supplied by the employment of penetration phosphor or field sequential color techniques. The extent to which color may serve to suppress or predispose the incidence of binocular rivalry is an unexplored issue. To the degree that it may be used as a distinguishing cue for sorting of visual images between the two alternative sources, it was suspected that judicious employment of color composition would help to combat rivalry.

FIELD-OF-VIEW

Field-of-view (visual subtense of the HMD image) is a design characteristic of HMDs whose effect on binocular rivalry is not known. Changes in HMD FOV, in effect, are changes in HMD display size, since viewing distance remains constant. There is no reason, based on theory or practical application, to expect FOV to affect the binocular rivalry phenomenon. It is conceivable, however, that small FOVs may produce greater HMD predominance due to increased contour strength of the HMD image relative to some fixed contour strength of the contralateral field. That is, smaller FOVs, (or smaller display size) for a given target image, result in smaller resolution cells defining the target. As long as the target remains sufficiently large for detection, the increase in resolution (smaller resolution cells) will increase the contour strength of the smaller FOV over that of the larger FOV. It was hypothesized, then, that within some undefined limit, smaller FOVs may result in greater HMD predominance than larger FOVs.

VISUAL ACCOMMODATION DISTANCE

The visual accommodation distance, or distance between the observer and the image plane of an optical system, is a variable feature of optical system design. The HMD visual coupling between the CRT and the user's eye can be configured to place the image plane at any convenient distance between the near accommodation limit of the eye and infinity. The placement of this image plane may be an influential factor in the causation or suppression of binocular rivalry. If the images reaching the two eyes are sufficiently different in terms of focal distance, the image at the distance to which an eye is not accommodated may be suppressed since it will be out of focus. Disparate visual accommodation distances may also serve as a cue to the source of the image and provide kinesthetic feedback for selective attention to either image. On the other hand, if the image planes are at identical distances, visual accommodation distance cannot serve as a cue as to the source of the image and binocular conflict rather than selective attention may predominate.

IMAGE FRAMING

HMD images can be presented by projecting an image on the helmet visor which serves as a combining glass. The image appears in this case to be suspended in space at optical infinity. An alternative is to package the combining glass in an eyepiece located in front of the observer's eye. This has the effect of making the image appear as if it were being viewed through a tunnel. Whether this variable affects binocular rivalry is unknown.

EYE DOMINANCE

Eye dominance refers to the fact that observers typically exhibit an eye preference. For example, if an object is viewed through an aperture with two eyes and then each eye is closed sequentially, the position of the object will remain aligned with the aperture with the dominant eye. It will shift laterally if the viewing eye is the non-dominant one. Eye dominance could be an important factor in the control of binocular rivalry.

Most HMDs are "right-handed", and from a producibility and logistics point of view it would be desirable if they could all remain common. However, if data suggest that left-handed HMDs be provided for left eye dominant observers, this fact would have to be incorporated into the HMD and helmet design.

AMBIENT SCENE COMPLEXITY

The stimulus strength of a field increases with amount of contour per area. Predominance of an HMD image of given contour strength will be dependent on the relative contour strength of the image presented to the contralateral eye. It is expected that an HMD image in competition with a contralateral image of relatively low contour strength will tend to predominate in the alternation cycle. Conversely, if the contour strength of the HMD image is low relative to that of the contralateral field image, the latter field will predominate in the alternation cycle. If the relative difference in contour strengths is large, one field may completely dominate the other.

TASK RELATED FACTORS

There is some evidence to suggest that task variables also affect binocular rivalry. When two images are alternating as the dominant one, it has been found that the rate of alternation decreases as time on the task increases. The meaning which the observer attaches to the images in each field also appears to affect the rivalry rate. These findings suggest that there is a relationship between experience with the task and the degree of rivalry.

RESEARCH ON HMDS AND BINOCULAR RIVALRY

Although a large body of research exists in the psychological literature on binocular rivalry, little data are available on HMD design and binocular rivalry. Only two studies were located which evaluated HMDs and binocular rivalry.

The first study, done by Jacobs, Triggs, and Aldrich (1970), was a qualitative laboratory and flight test evaluation of HMDs. In the evaluations, binocular rivalry was observed. It was reported that "rivalry effects were found, and there was at times a marked latency before a judgment could be made."

Observations made during the study regarding HMD design parameters and binocular rivalry were: 1) rivalry appeared to be greater when the fields of view of both eyes were of the same extent, 2) rivalry appeared to be greater when both eyes were accommodated to the same distance, 3) in a structured external scene, interaction between the two scenes was more marked and the HMD information was degraded, 4) rivalry was marked when the non-HMD eye was exposed to high ambient illumination, and 5) rivalry did not occur when symbolic information was displayed on the HMD.

As a result of the qualitative laboratory and flight test evaluation, Jacobs, Triggs, and Aldrich (1970), offered the following conclusions:

> The HMD image quality in this evaluation was adequate for displaying symbology and/or detailed pictorial information. At the present time, this image quality is considered to be at a level just below that of conventionally sized CRT displays. The picture brightness with complex images was adequate, and the resolution and shades of gray representation was comparable to other CRTs.
>
> The study indicated that interfacing the occluded display with the human perceptual system results in interference in the rate of information transmission. This type of display leads to problems of retinal rivalry which in the daylight flight domain were found to be significant. Perception of information from the HMD may occur

only after extended latencies. When using see-through displays, given a satisfactory balance between brightness entering the eye from the outside environment and the CRT brightness, alternation of attention between the external scene and the HMD scene can apparently occur at will. Despite the advantage of independent dark adaptation of the eyes in the occluded case, the preliminary and tentative indication is that the see-through device is preferred. This is because selective attention to each channel is less impeded in this system. This apparent superiority of the see-through display was probably heightened by the separation of the images arising from the different spectral composition of the HMD image and outside environment and the different focal plane of the two images.

A more detailed and systematic evaluation of such systems covering a range of system variables is warranted before these conclusions can be finalized.

The second study (Cohen and Markoff, 1973) investigated the relationship between binocular rivalry and visual performance for viewing a gunsight reticle in one eye and target imagery in the other eye, sequentially and with inter-ocular delay. It was hypothesized that if binocular rivalry existed, visual performance would be best when information was presented to only one eye and worst when presented to both eyes simultaneously. The results failed to confirm the hypothesis, and it was concluded that the influence of binocular rivalry on target recognition tasks is negligible with a see-through display. This finding confirms the observation of Jacobs, Triggs, and Aldrich (1970) that rivalry does not occur when symbolic information is displayed on the HMD.

The available literature on binocular rivalry permitted the definition of several HMD design parameters and environmental parameters that could affect binocular rivalry when using an HMD. The literature on HMDs confirmed that binocular rivalry occurs with HMDs when viewing complex scenes, but was insufficient to establish HMD design recommendations regarding binocular rivalry. The research program described in this report was conducted to establish the relationships between HMD design parameters and binocular rivalry.

RESEARCH APPROACH

A series of four laboratory studies and a modulation transfer function image quality analysis were conducted during the course of the study program. A qualitative laboratory evaluation was conducted preparatory to the conduct of formal laboratory research to get a "feel" for the binocular rivalry phenomenon with HMDs prior to construction of laboratory equipment for the formal research. A screening study which investigated 12 parameters was then conducted to determine which parameters affected binocular rivalry with HMDs. Next a parametric study was conducted to establish the functional relationship between binocular rivalry and the HMD parameters identified in the screening study as having a major impact on binocular rivalry. The final laboratory study was a validation study which compared selected HMD system configurations in realistic HMD and non-HMD tasks for binocular rivalry effects.

The image quality analysis evaluated the effects of ambient illumination, display luminance, combiner transparency, and angular display subtense on HMD video image quality using modulation transfer function analysis techniques. These five study tasks are described in the following sections of this report.

SECTION 2

QUALITATIVE EVALUATION OF BINOCULAR RIVALRY EFFECTS ON HMDS

INTRODUCTION

A qualitative laboratory evaluation of those factors and conditions thought to promote and control binocular rivalry and improve image quality in an HMD was conducted. The qualitative evaluation was conducted preparatory to the conduct of formal laboratory research. The purpose of the evaluation was to get a "feel" for the binocular rivalry phenomenon before committing funds to develop laboratory equipment for parametric research. In addition, evaluation of the effectiveness of a bifocular HMD was conducted.

HMD TASK APPLICATIONS

There are three major types of tasks for which the HMD might be used: one, superimposing a reticle on the HMD over a target in the ambient world; two, detecting or recognizing an object on the display with only secondary concern with events in the cockpit area or outside the aircraft; and three, correlating images on the display with objects in the outside world. The task of superimposing a reticle over a target requires that the reticle image on the HMD be seen simultaneously with the view of the outside world; the display must be located directly in front of the eye. The target recognition task does not require that the two scenes be seen simultaneously. By placing the display below the straight-ahead position of the eyes, a pilot can have binocular vision when viewing the outside world and may avoid the problem of binocular rivalry when looking slightly downward to view the display.

For the task of correlating images, the optimum placement of the HMD display is less obvious. The two scenes are to be correlated, but not superimposed. By placing the display below the straight-ahead position, the problems of binocular rivalry are reduced, but the observer must shift his eyes to perceive one scene at a time. Although it is not possible to view the scenes simultaneously, the alternative to shifting the eyes would be to shift the attention. However, with the superimposed views, the problems of binocular rivalry and degraded image quality of the display can be critical.

PLACEMENT OF THE HMD

By placing the upper edge of the displayed virtual image slightly below the straight-ahead viewing position, the exit pupil is still large enough to see the entire display. When looking straight-ahead, there is no longer an obstacle or impediment, and the outside world can be viewed binocularly at all times. The eyes can easily shift between the two scenes by an upward or downward movement. This position below the forward line of sight is referred to as a bifocular HMD.

METHODOLOGY

A laboratory simulation was set-up to reproduce the crucial features of HMD visual tasks. An HMD demonstrator and regulation pilot's helmet and face mask, shown in Figure 1, were modified so that either the standard (front) or the bifocular position of the display could be used. The HMD worn in the bifocular position is shown in Figure 2. A projector was used to present the image of an F-14 instrument panel onto a rear-view screen to simulate cockpit instruments. A high-intensity lamp was used to create high ambient illumination. A second projector was used to display ground scenes of the outside world onto a large screen slightly above the field of view at a distance of 20 feet. In addition, an IVC video recorder was used to put a moving scene of an attack on a bridge directly to the display.

TASKS

Several observers were employed. A variety of conditions were tried using the standard HMD and a bifocular HMD. One task required the observers to find a target on the HMD that they had been shown on the projected ground scene. In another task, the luminance of the cockpit instrument panel was varied. In a third task, the observers were required to note where lights were located in different parts of the room, including to the right rear, the side on which the display was mounted. Reliance in all cases was placed on subjective comments rather than quantitative measurements.

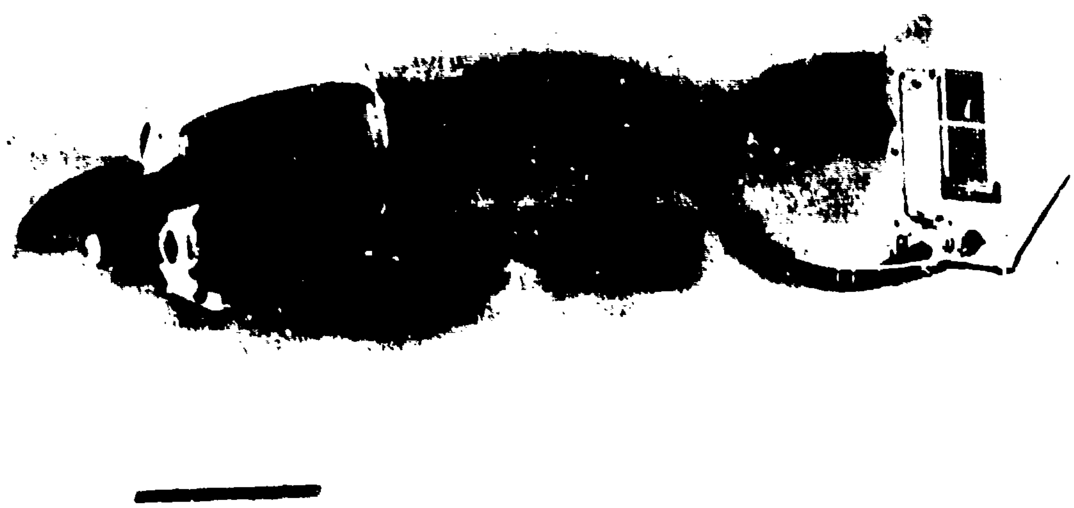


Figure 1. HMD demonstrator and pilot's helmet and face mask used in qualitative laboratory evaluation.

Figure 2. HMD worn in bifocular position

RESULTS

Visual Scene

The observers' ability to see the world outside the display, whether inside or outside the cockpit, was generally superior when a bifocular display was used. With slight, normal head movements, the observers' visual field could be increased with a bifocular HMD so that the blind area was slight. With a see-through HMD, the visual image of the outside world was slightly enhanced; although this introduced other complications because of the superimpositioning of the HMD and ambient scene images.

Binocular Rivalry

Binocular rivalry was experienced with the standard HMD arrangement. The occurrence of binocular rivalry was considerably less and more easily controlled with the bifocular HMD. With the bifocular display, either the observer looked at the outside world or at the display, so that no rivalry occurred between these two images. Since the bottom of the cockpit area was generally dark and evenly illuminated, no rivalry existed.

Image Quality

Image quality was degraded by the reduction in contrast and by the disruptive superimpositioning of patterns. With the standard HMD at either the see-through or the occluded display condition, the brightness of the displayed image was mixed with the brightness of the ambient scene. When the outside scene was too bright, the use of a filter over the open eye helped eliminate the degrading effect of the ambient scene luminance.

Ambient Luminance

A high-intensity light was used to simulate ambient illumination of approximately 6000 foot-lamberts and was placed within less than three feet of the viewers' eyes on the side opposite of that of the display. Perception of the display with both bifocular and standard HMDs was affected. The effect came from the degradation of image quality from the bright light. A 15 percent transmission filter over the open eye and a slight turning of the head was sufficient to minimize this effect.

Eye Dominance

Image quality and binocular rivalry were affected by the relative luminance of the two images. A critical factor affecting perceived image quality of the HMD was the difference between the viewer's two eyes. To see the display clearly with the least effects of degraded image quality or binocular rivalry taking place, the display had to be viewed through the dominant eye.

Scene Dynamics

Presentation of a moving or static scene on the HMD had no observable effect on the incidence of binocular rivalry.

GENERAL CONCLUSIONS

The qualitative evaluation verified the occurrence of binocular rivalry with HMDs and showed it to be influenced by a number of HMD design related parameters. These findings were used to establish the requirements for additional laboratory research discussed in the following section of this report.

SECTION 3

QUANTITATIVE LABORATORY EVALUATION OF BINOCULAR RIVALRY EFFECTS ON HMDs

GENERAL APPROACH

Because of the large number of variables thought to be involved in the binocular rivalry phonemenon and since little knowledge was available as to how these variables interact, the research strategy was to narrow the number of combinations by a series of successively refined observations and experiments.

The parameters selected to define the initial experimental space are shown in Table 1. These parameters were selected from a review of the

TABLE 1. CANDIDATE PARAMETERS AND HMD DESIGN CHARACTERISTICS

Parameter	HMD Design Characteristic
Resolution	CRT Resolution and Optics
Field of View	Display Size and Optics
HMD Luminance	CRT Luminance and Optics Losses
Ambient Scene Luminance	Visor Density
Percent Transparency	Combiner
Framing	Image Appears framed in Eyepiece as Opposed to Visor projected type HMD
Color	CRT and Filters
HMD Accommodation distance	Optics
Ambient Scene Accommodation distance	N. A.
HMD Eye Presentation	Helmet and Latch
HMD Contrast	CRT Contrast
Ambient Scene Complexity	N. A.
HMD Eye Position (Bifocularity)	Helmet Latch

binocular rivalry literature, the qualitative evaluation, and exploratory experimentation using the HMD simulation equipment developed for this research.

A single factorial replication using a complete range of values for all the candidate variables would require thousands of trials. A formal experiment of this magnitude would be very expensive and would likely include variables that are non-contributory. Therefore, an increasingly refined set of observations that sampled combinations of variables under controlled laboratory conditions was undertaken to identify critical factors and to eliminate trivial variables.

The objective of the data collection plan was to reduce the number of observations without losing the desired information. To achieve this, data collection was divided into three phases: 1) a screening study to determine those parameters which contribute significantly to the binocular rivalry phenomenon, 2) a parametric study to determine the functional relationship between binocular rivalry and the significant parameters determined from the screening study, and 3) a validation study to determine the relationships of parameter values found to distinguish between levels of binocular rivalry and the effect of these parameter values on target recognition and tracking tasks.

LABORATORY EQUIPMENT

The research requirements dictated a highly versatile equipment configuration to independently manipulate a large number of parameters. This was accomplished by using optical projection techniques to simulate the two visual scenes (HMD and ambient) and a variety of optical and mechanical controls to manipulate experimental variables as well as to control extraneous sources of variation. Two slide projectors were employed to project separate images onto two screens. Figures 3 and 4 show the research apparatus. Figure 3 shows an overall view of the equipment. The slide projectors, mounted on tripods, cannot be seen as they are behind the rear-projection viewing screens. Figure 4 shows a close-up view of a beam-splitter which simulated the HMD display surface and part of the optical system used to manipulate HMD accommodation distance.

A description of key elements of the equipment is given below as well as the methods for simulating HMD characteristics and manipulating experimental variables. Where modifications of the equipment were made for a particular study, those modifications will be described in the later discussions of each study. The optical equipment required to provide simulation of the two images and control of the experimental variables was comprised of rear-

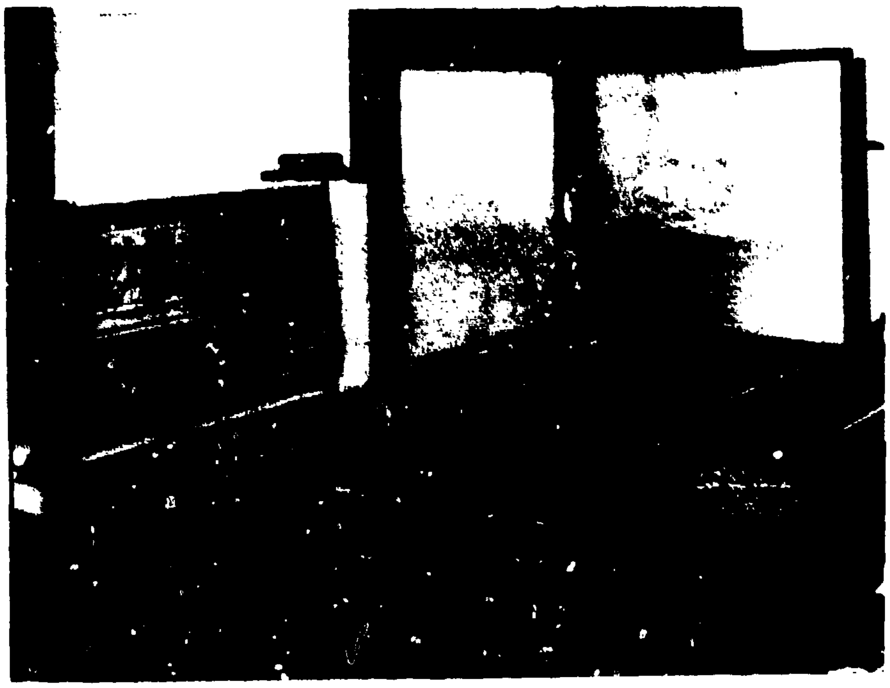


Figure 3. Research apparatus, overall view.

projection screens, movable slide projectors mounted on tripods, optical lenses, filters, and beam splitters. Each is described below.

Projection Screens

Two 30- by 30-inch square rear-projection screens were made by a spray technique depositing a thin uniform translucent diffusing coating onto one side of 0.0125-inch thick clear acrylic sheet. The screens were supported in a self-standing metal frame that could be raised or lowered to a desired height. The screen gain was measured and found to be 4. This is defined as a ratio of the on-axis brightness of the screen display to the brightness of a perfectly diffuse reflecting screen. Higher gain screens were not chosen because of the greater fall off in brightness at the edges of the screen. This is an important factor in maintaining uniform brightness across the simulated display because the display-to-subject distance was small (15.5 inches) and the angle that the light must deflect at the edge of the screens was large (40 degrees). The on-axis measured resolution of the screen was 202 TV lines per inch.

Figure 4. Research apparatus, close-up of beam splitter which simulated HMD display surface.

Projectors

Two 500-watt Kodak Carousel projectors with remote controls were used to project the images onto the screens. They were selected because of their flexibility, reliability, and brightness output. To limit the physical space required to set up the apparatus and to get maximum brightness and maximum resolution, 4-inch focal length Kodak Raptnar lenses were used. The resolving power of each lens was measured and compared to manufacturing data to ensure that image resolution was not equipment limited. Lens resolutions ranged from 6,100 to 12,200 optical line pairs, which exceeds the requirements of simulated display resolution values. The open-gate (no film) brightness for the maximum projection distance of 6.5 feet was measured at 560 fL on the screen.

Image brightness on the screen was controlled by selecting neutral density gelatinous filters and placing them in the projection path in conjunction with a variable iris that was used for precision adjustment while the image was measured with a photometer. This measurement was accomplished by placing the photometer in the viewing position of the subject to account for all optical elements in the visual path.

Beam Splitters

The HMD was simulated by using beam splitters to deflect the HMD screen image directly in front of one eye. Figure 5 depicts a top view of this arrangement.

The observer looked straight-ahead, and with one eye viewed the scene representing the helmet-mounted display (D). This portion of the apparatus was movable so that it could be presented to either eye. The other eye also looked straight ahead, and viewed the image representing the ambient scene (E). The degree of transmission was obtained by varying the density of the partially silvered mirror (M) through the use of filters placed behind the mirror and cut congruent to mirror dimensions. The beam splitters were metallic coated glass. The coating was deposited in a thin uniform layer so that in position at 45 degrees to the visual path the reflectance was 90 percent. The transmission of the beam splitters without filters was 10 percent. The shapes of the beam splitters were designed to provide, within the limits of practicality, the unframed HMD. The unframed display was simulated by cutting the beam splitters into ellipses of proper sizes which, with the proper combination of optics and HMD image size on the screen, represented various HMD fields of view. For the framed HMD configuration a large beam splitter was employed which completely occluded the ambient scene (at zero transmission) to the HMD eye. In this case, field of view was manipulated by varying the projected image size.

Accommodation Optics

Lenses were used to present images at focal distances of 30 inches and infinity. Appropriate screen-to-subject distances were chosen in conjunction with projector-to-screen distances to provide the widest field of view required. To make the image collimated (appear to come from infinity),

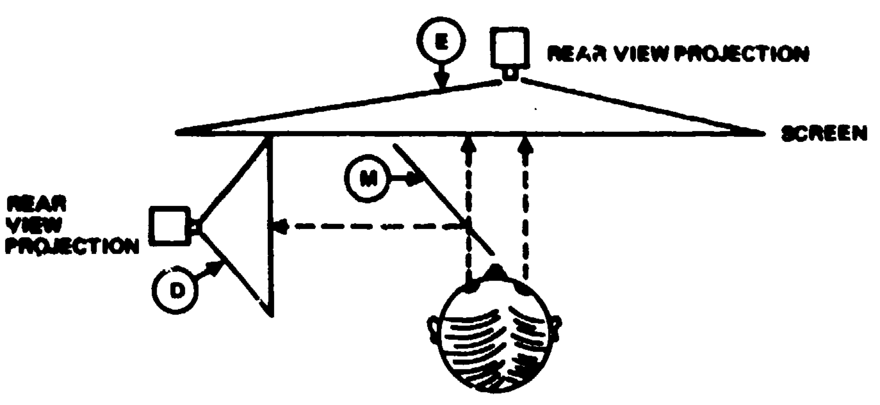


Figure 5. Top view diagram of research apparatus.

simple magnifying ophthalmic lenses were used, mounted in eyeglass frames. These were 2.5 diopter lenses for both eyes to correct for the screen-to-subject distance of 15.5 inches.

To simulate an accommodating distance of 30 inches for the HMD scene and infinity for the ambient scene, a second large negative correcting lens was inserted into the HMD visual path. To make the HMD scene appear at infinity and the ambient scene at 30 inches, no lenses were used with the front screen, and the negative lens was used with the side HMD screen. The corrective lenses restricted the field of view to 50 degrees. The corrective lenses were 6 inches in diameter.

Control Device

A method for obtaining a quantified criterion measure of binocular rivalry was developed based on the subjects' subjective evaluation of HMD visibility during a 1-minute trial. The apparatus provided a measure of the proportion of time in seconds that the HMD and ambient scenes were predominant during the task. The subject provided his evaluation of HMD scene visibility i.e., the degree to which the HMD scene was visible, by moving a linear control lever from full back, to indicate the HMD scene was not visible at all, through full forward, to indicate 100 percent HMD scene visibility. The control device was a rectilinear potentiometer, with a .5-inch stroke producing a control signal which was computed using a Miniac computer as the integral of stick deflection from the zero position. The stick was spring mounted and came to rest at the center of its stroke which corresponded to a score of 50 percent visibility of the HMD scene. The 50 percent rest position provided subjects a reference point from which to base HMD visibility judgments while the spring tension on the control lever provided kinesthetic feedback of control lever position.

In addition to the HMD visibility scores, the Miniac computer was programmed to record the cumulative time in seconds that the control device was above the 90 percent HMD visibility position of its stroke or below the 10 percent visibility position. A separate computer cumulative timer was activated when either of these thresholds was crossed. These scores provided a measure of alternation predominance of the two visual fields.

MANIPULATION OF INDEPENDENT VARIABLES

A description of the methods for manipulation and control of the experimental variables is provided below. Operational definitions of the variables, values of levels selected, and the rationale or equipment limitations for selected values will be discussed separately under each study heading.

HMD Resolution

HMD display resolution levels were simulated by defocusing the projected HMD images. A resolution chart was placed in the projector and defocused until the required resolution could be read off the display screen. Without changing focus, The HMD scenes were interchanged with the resolution chart, and the defocused scenes were photographed at each resolution value. By this rephotographing method, the simulated HMD resolution values were retained on film, obviating the requirement to manipulate projector focus during the actual running of the experiment. To change HMD resolution, it was only necessary to change slides.

HMD Contrast

Contrast was manipulated by rephotographing projected slides with varying amounts of ambient lighting to wash out contrast. Average image intensity was matched for all conditions. The contrast levels were photographed for each HMD scene at each resolution level on both color and black and white film.

HMD Field-of-View

Field-of-view was manipulated by varying the size of the projected HMD image. Because of certain combinations of optics and HMD screen-to-subject distances necessary to vary accommodation, HMD screen image size was not constant for all HMD accommodation conditions to produce a given FOV value. Consequently, it was necessary to calculate the screen image dimensions for FOV values for each HMD accommodation condition. The projector-to-screen distances required to achieve the necessary image size for each FOV-accommodation condition were then marked so that the projectors could be easily moved to the appropriate distance when required. To maintain proper projector/screen alignment when changing projector distances, lengths of 3/4-inch plywood, approximately 3 feet in width by 8 feet in length, with runners on one side along which the projector tripods could be moved, were secured to the floor.

Accommodation

Accommodation distance for both screens was manipulated by combinations of optics and subject-to-screen distances. For the ambient scene screen, only two screen positions were required, 15.5 and 30 inches. At the 15.5 inch screen position, subjects were required to wear eyeglasses with 2.5 diopter lenses. The focal length of these lenses was 15.5 inches and the eye was accommodated at infinity when objects were viewed at that distance.

The positive and negative correction lenses which were required to accommodate the HMD scene at infinity when the ambient scene was accommodated at 30 inches and to accommodate the HMD screen at 30 inches when the ambient screen was accommodated at infinity, necessitated different subject-to-screen distances because of the effect of their insertion into the

HMD scene visual path. Appropriate HMD screen distances were calculated and marked on the apparatus table so that the screen could be correctly placed for any required HMD-ambient accommodation condition combination.

Framing

Framed and unframed HMD configurations were manipulated by changing the size of the beam splitters presented to the eye. In the unframed condition, beam splitters were cut in the shape of ellipses and permanently glued to a round narrow shaft which was inserted into a support arm. The size of ellipses was determined by the screen image size for the various HMD fields-of-view and was just large enough to contain the entire HMD 4:3 rectangular format when placed just in front of the viewing eye at a 45 degree angle. Thus, in the unframed configuration, only that portion of the ambient field which was covered by the beam splitter was occluded (at zero percent transparency) to the HMD eye. The area of ambient field occlusion varied, of course, with HMD field-of-view, or beam splitter size. Occluded ambient field area was 33, 67, and 100 percent for the 9/16 x 13/16, 1-1/8 x 1-5/8, and 1-3/4 x 2-1/2 inch beam splitter dimensions representing, respectively, the 15, 30, and 45 degrees HMD field-of-views which were investigated.

A large (7.5 x 10.0 inches) beam splitter, shaped as a right triangle with rounded angles, was used to simulate the framed HMD configuration. For this condition, the entire ambient field was occluded to the HMD eye at zero percent transparency.

HMD and Ambient Luminance

Luminance values were manipulated by inserting filters into holders which had been attached in front of the projector lenses for this purpose. Fine adjustments, which were necessitated by the varying densities of the photographic imagery, were accomplished by varying the aperture of the iris diaphragms which had been mounted between the projector lenses and the filter holders.

A photometer was used to control luminance values while making projector adjustments. A large photometer aperture was used to obtain an average scene luminance reading. For the HMD scene, photometer measurements were taken off the beam splitter so that all optical surfaces in the subjects' visual path were accounted for. Only that portion of the ambient scene upon which the HMD scene was directly superimposed was measured to obtain ambient scene values. This was done to control for luminance variance across the ambient scene imagery.

Percent Transparency

Manipulation of this variable was accomplished by fixing variable transparency filters or opaque masks to the obverse side of the beam splitters to reduce transparency downward from the 10 percent limit of the beam splitters.

Eye Presentation (Dominance)

The apparatus was constructed to allow presentation of the HMD to either eye. To accomplish this, the HMD projector and screen were set up on either the right or left side of the apparatus table. The beam splitter support arm was rotated 90 degrees to position it at a 45 degree angle to the appropriate eye. Accommodation optic supports were located on both the right and left side of the beam splitter.

Ambient Scene Complexity

The complexity of that portion of the ambient scene on which the HMD scene was superimposed was varied by shifting the position of the ambient scene on the ambient scene projection screen.

Color

HMD imagery was photographed in both color and black and white. Ambient scene imagery was photographed in color only.

SCREENING STUDY

Purpose

The purpose of the screening study was to determine which of a large number of parameters had a significant effect on binocular rivalry in helmet-mounted displays. Twelve factors were identified as potentially important contributors. Even when these 12 factors are limited to two levels each, a single replication of a complete factorial design would require 4096 observations. The increase in precision of estimates accruing from the factorial arrangement of a study of this magnitude far exceeds necessary requirements and, indeed, is likely to uncover statistically significant effects which are, for practical purposes, trivial. Of the 4095 degrees of freedom for the total factorial design, 401 degrees of freedom are associated with interactions of four or more factors. Since interactions of four or more factors typically have no effects on human performance, to collect data for the purpose of ferreting out these nonexistent effects is wasteful. Therefore, a fractional factorial for selected factor combinations was used. In an experiment formed from less than one replicate it is not possible to estimate each effect separately. Hence, a quantity calculated to estimate a particular effect will in general depend also on the true value of one or more other effects, usually interactions. A good fractional factorial design is one which estimates each main effect, and if possible, each two-factor interaction, in such a way as to be intangled (aliased) only with high-order interactions involving three or more factors.

In a recent analysis of human factors experiments based on 121 articles and 239 statistical analyses found in the journal Human Factors between 1958 and 1972, three factor interaction effects were considered negligible in over 95 percent of the experiments. Moreover, the more factors studied in a single experiment the smaller was the proportion of variance accounted for by such interactions (Simon, 1973). It is apparent that the assumption that three-factor interaction and higher order interactions are negligible is the most parsimonious one to make.

Several fractional factorial design alternatives exist in which main effects and two-factor interactions are aliased with three-factor and higher-order interactions. Design selection was based on three considerations: 1) total number of data points (size of the fractional replication), 2) number of subjects required, and 3) number of observations required per subject.

The design selected was a 1/32 fractional replication of a complete 2^{12} factorial arranged in 16 blocks (subjects) of eight observations per block requiring a total of 128 observations. The number of data points required by this design was considered sufficiently large to ensure precise point estimation and powerful significance tests, while retaining economy of experimental effort. Fractional factorials may be arranged with or without subject blocking. If subjects are not used as blocks, however, two advantages are lost. First, a large number of subjects would be required, one for each data point. Such a large sample of subjects was not available. Second, when large inter-subject variability in performance is expected (pilot studies indicated this to be the case), blocking increases precision of treatment effect estimation and consequently the power of statistical tests, since the variance attributable to subjects can be partitioned from the error term. The design selected used a large enough subject sample to reasonably ensure random error distribution while keeping the number of observations per block within reason. This latter consideration was based on the observation that subjects may learn, with time, to voluntarily control predominance of alternation of the disparate images in a binocular rivalry situation. That is, there may be a learning effect with training under binocular conflict. To avoid prolonged experience with the phenomenon, block size was kept small.

Since all three-factor and higher-order interactions were assumed negligible, all main effects and two-factor interactions aliased with the three-factor and higher-order interactions were measurable. In the selected design, all main effects and 58 of the 66 two-factor interactions were measurable. Information on eight of the two-factor interactions was sacrificed to make use of the advantages of blocking. Obviously, many of the 66 two-factor interactions could be eliminated as having any potentially important effect, and which interactions could be sacrificed was under partial control of the experimenter. The experiment was organized so that the eight unmeasurable two-factor interactions were those which were assumed a priori to be non-existent. These are identified later.

Imagery

Ambient scenes (non-HMD imagery) consisted of two scenes, an F-14 front cockpit (Figure 6), and a ground scene of the Hughes Aircraft landing strip photographed from a hill adjacent to the facility (Figure 7). The cockpit and ground scenes were used for the 30 inch and infinity ambient scen›

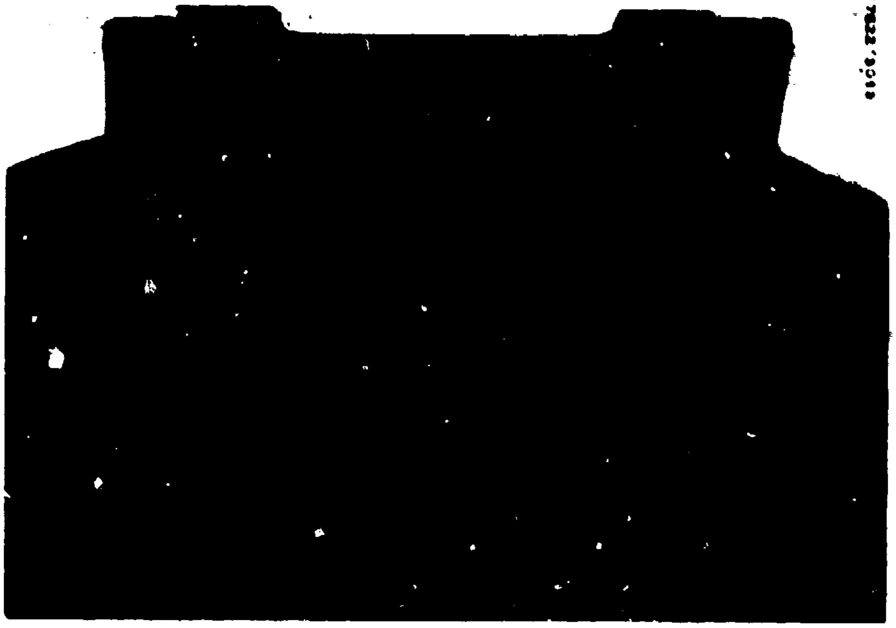


Figure 6. F-14 front cockpit ambient scene.

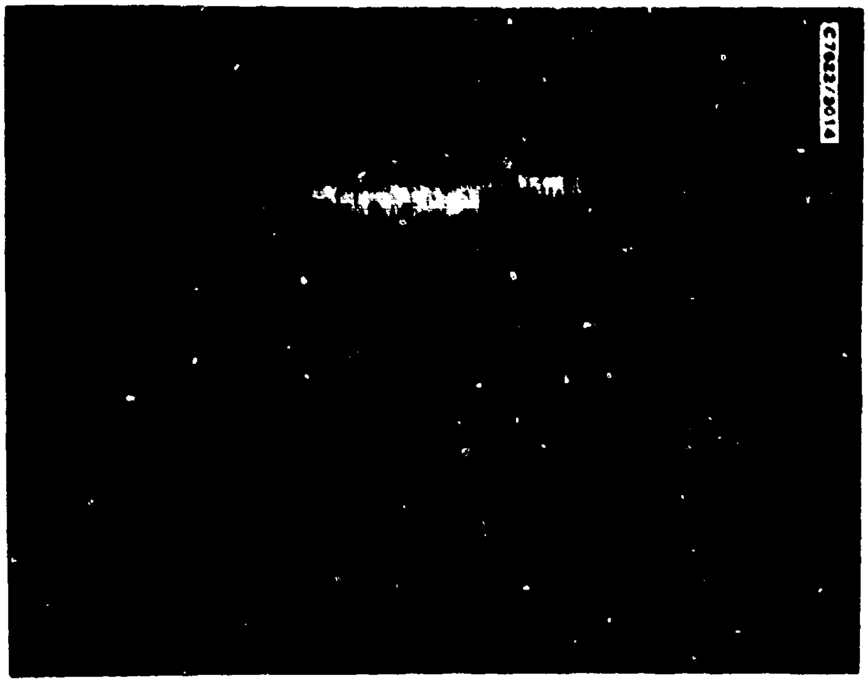


Figure 7. Ground scene ambient scene.

accommodation conditions, respectively. The HMD scene was taken from a portion of the ambient scene representing a sensor field-of-view of 18 degrees and included a helicopter, located adjacent to the runway, as a target image. Figure 8 shows the HMD scene.

Since the question under investigation was the effect of binocular rivalry in HMD systems, and because the criterion measure of binocular rivalry was the degree of HMD image visibility (contrasted with a target recognition task), it was not considered necessary to use more than one HMD scene. To use additional HMD scenes would have entailed a larger effort in collecting and processing the additional imagery as well as introduced problems of control over variation in image parameters (resolution, contour strength, contrast, etc.) across the various scenes. This additional expenditure of experimental effort was not deemed warranted.

Operational Definitions of Independent Variables

Table 2 shows the 12 parameters and the levels of each investigated in the screening study.

HMD resolution was defined as the number of active TV lines across the vertical dimension of the display simulated by defocusing the slide projector lens. The values used (165 and 630 TV lines) were considered to represent a minimally acceptable resolution limit and an upper limit currently operational. Figure 8 shows the HMD scene at the two resolution values for the black and white condition.

HMD field-of-view was defined as the size of the displayed image. The values chosen, 15 and 45 degrees of arc at the subject's eye, encompass the range currently used in HMD systems.

HMD transparency was defined as the percent of light from the ambient field which reached the HMD eye and was simulated with partially silvered beam splitters in conjunction with filters. While large upper values might have been used, the beam splitter limit of 10 percent was considered a maximum for high ambient illumination ambient scene conditions. The occluded, zero percent, was an obvious lower bound.

HMD framing was defined as presenting the image on a beam splitter just large enough to contain the image (unframed) or on a large beam splitter which totally occluded the ambient scene to the HMD eye (framed).

HMD color was defined as Kodachrome or black and white positive transparencies. Figure 9 shows the simulated HMD color image at the high resolution, high contrast condition.

HMD eye presentation was defined as presentation of the HMD image to either the right or left eye.

a. 630-line resolution

b. 165-line resolution.

Figure 8. HMD scene at the two resolution levels investigated.

TABLE 2. PARAMETERS AND VALUES USED IN SCREENING STUDY

Parameter	Parameter Values
HMD Resolution	165 and 630 active TV lines
HMD Field of View	15 and 45 degrees
HMD Transparency	Zero and 10 percent
HMD Framing	Framed and unframed
HMD Color	Monochrome (black and white) and Color
HMD Eye Presentation	Dominant and Non-dominant eyes
HMD Luminance	0.28 and 8 fL
HMD Accommodation Distance	30 inches and infinity
HMD Contrast Ratio	4.6 and 21.9 $\left(\frac{B_{max}}{B_{min}}\right)$
Ambient Scene Luminance	0.28 and 8 fL
Ambient Scene Accommodation Distance	30 inches and infinity
Ambient Scene Complexity	Low and High (relative)

HMD luminance was defined as the average scene luminance, in foot-Lamberts, measured off the beam splitters. The lower (0.28 fL) value was selected as a minimally acceptable lower limit. A higher upper limit would have been desirable, but higher values were precluded because of the limit imposed by projector output and by the densest transparency. However, since relative differences were considered of more interest than absolute values at this stage of experimentation, the limits imposed (0.28 and 8.0 fL) were considered acceptable.

HMD accommodation was defined as the distance at which the HMD image is brought into focus (accommodated) by the eye. The levels selected (30 inches and infinity) are operational value limits.

HMD contrast was defined as the ratio of the brightest image area to the darkest averaged across all the HMD transparencies. Contrast values could not be predetermined since transparency contrast is a function of

Figure 9. HMD color scene.

photographic materials and procedures such as film type, initial exposure, processing solutions, processing time, temperature, etc., and is highly variable. Contrast ratio values were measured after final processing. The values obtained, 4.6 and 21.9, were considered adequate to determine the effect of contrast on binocular rivalry. Figure 10 shows the high and low contrast values, at the high resolution, black and white HMD configuration.

Ambient scene luminance was defined as the average luminance of that portion of the ambient scene upon which the HMD image was superimposed. The high luminance value (8.0 fL) was limited by projector output and transparency density. The lower 0.28 fL value was selected to be the same as the lower HMD luminance value.

Ambient scene accommodation was defined as the distance at which the ambient scene image was accommodated by the eye. The selected levels, 30 inches and infinity, were chosen to represent a standard cockpit viewing distance and out-the-window viewing, respectively.

Ambient scene complexity was defined as the amount or number of contours per area in the ambient scene image upon which the HMD image was superimposed. Since the number of contours could not be precisely defined due to the use of real-world rather than artificial, controlled imagery, the complexity values are relative rather than absolute. For each ambient scene, high and low complexity areas were selected. Low complexity areas contained almost no contours in each case.

a. 21.9 contrast ratio.

b. 4.6 contrast ratio

Figure 10. HMD scene at the two contrast levels investigated.

Dependent Measures

The three measures of binocular rivalry recorded from the operator's response device are defined below. Percent of HMD visibility was defined as the average response lever position, on a linear scale from zero to 100 percent, over a 1-minute trial, as recorded by the Miniac computer in 10ths of a percent.

HMD image predominance was defined as the total number of seconds the response lever was in the 90 to 100 percent position during the 1-minute trial, measured in 10ths of a second.

Ambient scene image predominance was defined as the total number of seconds the response lever was in the zero to 10 percent position during the 1-minute trial, measured in 10ths of a second.

Subjects' Task

Subjects were requested to evaluate the visibility of the helicopter in the HMD scene by moving the response lever forward (increased visibility) or backward (reduced visibility). Subjective evaluations of the perceptual process during binocular rivalry when viewing complex scenes is difficult, since parts of both scenes are perceived, and it is not always possible to determine which parts belong to which scene. It was believed then, that subjects would have extreme difficulty in evaluating the visibility of the total HMD scene and, consequently, scores would be highly variable and insensitive to manipulation of experimental parameters. To test this hypothesis, a pilot study was conducted to compare the task of whole scene evaluation against the task of evaluating a specific, recognizable target, under various conditions. As expected, the whole scene visibility evaluation task produced highly variable response scores and failed to discriminate between different treatment conditions. The helicopter visibility evaluation task, on the other hand, produced consistently reliable scores which were highly sensitive to manipulation of HMD conditions.

Research Design

A 1/32 fractional replication of the full 2^{12} factorial design was employed, arranged in 16 blocks of eight observations per block. Each of the 16 subjects was presented eight of the 128 treatment combinations of the 1/32 fractional replication. Manipulation of HMD eye presentation was the most time consuming variable change during the running of the experiment, since it required dismantling and reassembling the optical system. For this reason, eye presentation was systematically assigned within blocks, presenting four of the eight treatment combinations first to one eye and the remaining four to the other eye, rather than randomly assigning all eight treatments within blocks. This was done to facilitate procedural efficacy as the optical system change was then required only once for each subject as opposed to multiple changes if treatments were randomly assigned. Eye presentation order was counter-balanced across subjects. The four treatment combinations within each eye presentation condition were randomized, and subjects were randomly assigned to blocks. Table 3 shows the design model.

TABLE 3. DESIGN MODEL FOR SCREENING STUDY

Blocks							
1	2	3	4	5	6	7	8
(1)	bcdeghjkm	ghjk	bcdem	abcdefgh	afjkm	abcd-fjk	afghm
abcd	aeghjkm	abcdghjk	aem	efgh	bcdfjkm	efjk	bcdfghm
adefghjk	bfm	cdef	bfghjkm	abjk	acdeghm	abgh	acdejkm
abefghjk	acdfm	abef	acdfghjkm	cdjk	beghm	cdgh	bejkm
bcghjklm	del	bclm	deghjkl	adefjklm	abcfghl	adefghlm	abcfjkl
adghjklm	abcel	adlm	abceghjkl	bcefjklm	dfghl	bcefghlm	dfjkl
bdeflm	cfghjkl	bdefghjklm	cfl	acghlm	abdejkl	acjklm	abdeghl
aceflm	abdfghjkl	acefghjklm	abdfl	bdghlm	cejkl	bdjklm	ceghl
9	10	11	12	13	14	15	16
acdefgjl	abfhklm	acdefhkl	abfgjlm	bhjl	cdegklm	bgkl	adehjlm
befgjl	cdfhklm	befhkl	cdfgjlm	acdhjl	abegklm	acdgkl	bcehjlm
ahkl	abcdegjlm	agjl	abcdehklm	bcdefgkl	fhjlm	bcdefhjl	fghlm
bcdhkl	egjlm	bcdgjl	ehklm	aefgkl	abcdfhjlm	aefhjl	abcdfghlm
abdefhkm	acfgj	abdefgjm	acfhk	cgkm	bdehj	chjm	bdegk
cefhkm	bdfgj	cefgjm	bdfhk	abdgkm	acehj	abdhjm	acegk
abcgjm	adehk	abchkm	adegj	defhjm	bcfgk	defgkm	bcfhj
dgjm	bcehk	dhkm	bcegj	abcefhjm	adfgk	abcefgkm	adfhj

Subjects

Fourteen male and two female Hughes engineers served as subjects. One additional subject participated in the experiment, but his data were not used in the statistical analysis, because he had been previously trained in the use of special binocular optical devices which introduced rivalry and had acquired the ability to see either image at will. Consequently, his HMD visibility scores remained invariently high across treatment conditions.

Apparatus

The experimental apparatus was used as described in the Equipment Section above.

Procedure

Subjects were brought into the laboratory, seated at the apparatus, and given a copy of the experiment instructions. The instructions are contained in Appendix B of this report. After reading the instructions, the apparatus was adjusted and aligned for each subject to ensure that the HMD scene was properly framed in the beam splitter and superimposed on the ambient scene in the correct position. Once these adjustments were made, the following procedure was employed on all training and test trials.

A subject was asked to place his chin in the chin rest, close his eyes, and signal the experimenter when he was ready to begin. The experimenter turned off the ambient room illumination, cleared the computer, and said, "One, two, three, start", simultaneously pressing the computer START button and a stop watch with his verbal command "start." At the command start, the subject opened his eyes and began moving the response device according to his subjective judgment of the HMD scene helicopter visibility. After 60 seconds, the experimenter said "Stop" and pressed the computer HOLD button to lock in the criterion scores. Percent visibility and field predominance scores were read from the computer digital readout display by turning a dial to the appropriate channel. Scores were recorded on pre-prepared data sheets.

Two 1-minute trials were given for each treatment condition during test trials to provide an estimate of reliability of the binocular rivalry criterion measures. Following the two 1-minute trials, ambient room lighting was turned on and subjects were asked to take another seat in the laboratory, away from the apparatus, so that the experimenters could make the appropriate changes for the next condition. The pre-prepared data sheets listed parameter levels for each treatment condition in equipment terms to expedite the required apparatus changes. Because of the large number of parameters, all of which required adjustment on every trial, extreme care was taken to ensure that appropriate parameter combinations were set up. One experimenter read the required conditions to the second experimenter while the latter made the adjustments. The two worked together making luminance changes, one making projector adjustments and the other reading luminance values on the photometer. After all adjustments were made, one experimenter called them out a second time while the other doublechecked the equipment. Equipment changes took between 6 and 8 minutes. Once the equipment was double checked, the subject was reseated at the apparatus to begin the next trial.

Eight 1-minute training trials (at four conditions) were given to familiarize the subjects with the procedure, the response device, and the binocular rivalry phenomenon. Because of the time involved, elaborate equipment adjustments were not made between training trials. Instead, resolution was changed by defocusing the projector lens, and luminance ratio and background complexity were arbitrarily adjusted merely to provide the subject experience with various degrees of HMD image predominance and to provide the experimenter an estimate of reliability of the subjects' responses. The subjects were instructed to judge the visibility of the HMD target image independent of the quality of the image. Before each trial, the subjects were shown the HMD scene without the ambient scene so they could judge HMD image percent visibility — not HMD scene image quality.

After completing the test trials, eye dominance of the subjects was measured. The significance of the eye presentation parameter was not presentation to the right and left eyes, but was presentation to the dominant and nondominant eyes, which differs between subjects. It was necessary, therefore, to determine the eye dominance, if any, of each subject. No unambiguous technique for measuring degree of eye dominance is known. However, for those subjects who exhibit eye dominance, techniques are available to determine which is the dominant eye. Several methods were employed to make this determination. First, an attempt was made to use the experimental apparatus to determine eye dominance. The rationale was: given two stimuli matched for contour strength (e.g., two slides containing the letter "R", one of which is reversed), any difference in percent visibility scores could be attributed to eye dominance. However, this method also proved to be ambiguous, and since simpler and less time consuming techniques were available it was not used.

The method used employed a cardboard viewing device, shaped like a flat, rectangular box, open at one end. A sketch of the device is shown in Figure 11.

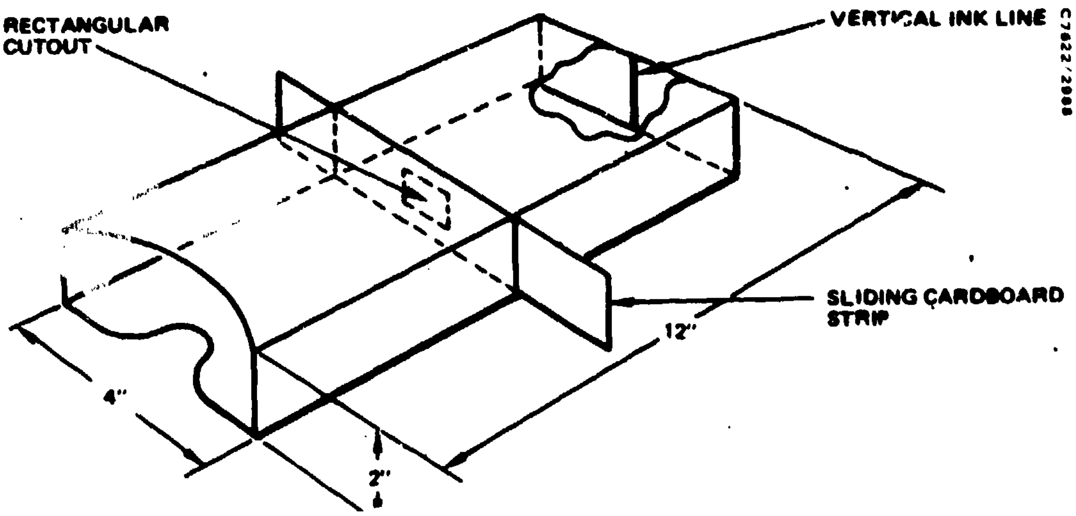


Figure 11. Eye dominance test device.

The subjects were asked to hold the device up to their face covering their eyes and focus on a vertical ink line drawn on the rear panel. The object was to move the slidin .rdboard strip so that the rectangular cutout was centered over the li With the eyes accommodated at the vertical line, two images of the rectangular cutout are seen, since it is out of focus. If eye dominance is present, one of the cutout images will appear more salient, and this image will be centered on the vertical line. The experimenter then examines the position of the cutout relative to the center line of the box. If the cutout was off center to the right, the subject was considered right eye dominant. Off center to the left implied left eye dominance. Subjects who have little or no eye dominance will see both cutouts as equally salient. In such cases, subjects were asked to make a forced choice to place them in either the left or right eye dominant group.

The ambiguity of eye dominance determination method arises from those individuals who have only a slightly dominant eye or where neither eye is dominant (at least not measurably so with available techniques). With such individuals, a second, simple technique (used by the Los Angeles Police Training Academy for establishing eye dominance for pistol training) was used as an attempt to reduce ambiguity. Subjects were asked to focus on a small object on a far wall, extend either hand, and with both eyes open, encircle the object within a circle made by the forefinger and thumb of the extended hand. By closing just one eye and then the other, eye dominance is established by determining with which eye the object is still encircled. This method also produced ambiguous results with some subjects, but with the two methods combined all subjects were identified as either right or left eye dominant, five of the 16 subjects being borderline cases. The final breakdown was nine right-eye dominant and seven left. Eye dominance was determined after all data collection trials were completed.

Results and Discussion

When more than one measurement is taken on the same subject under the same treatment condition, it is not statistically valid to consider each measure as independent for analysis purposes. Two courses of action are available: 1) the scores may be averaged and considered as one score, or 2) independent analyses may be performed on each score. Both methods were used to analyze the two scores (trials) obtained for each subject-condition combination.

First, two separate analyses of variance were performed, one on the first score obtained for each subject under each condition, and one on the second score. This was done in order to obtain an estimate of reliability of the criterion measure. A reliable measure should produce essentially the same results in terms of significant effects and rank order of effects in terms of proportion of variance accounted for (Eta squared), and this proved to be the case. Table 4 shows a comparison of first and second score analysis mean squares and Eta Square values for the HMD percent visibility dependent measure. The complete analyses are not shown.

The same seven main effects were identified as significant in each analysis. It can be seen that the mean squares for significant main effects, subject effects, and error differ very little between the two analyses. Overall grand means are separated by less than two percentage points. The separate analyses for HMD and ambient scene predominance criterion measures showed similar reliability.

Since the criterion scores proved to be highly reliable, either analysis could be used to interpret the data. To use only one of the scores, however, would mean to discard half the available data. When more than one estimate of parametric effects is available, the best policy is to pool

TABLE 4. COMPARISON OF FIRST AND SECOND SCORE ANALYSES FOR HMD PERCENT VISIBILITY

	First Score		Second Score	
	Mean Square	Percent Eta^2	Mean Square	Percent Eta^2
Background Complexity	24,736.44	24.7	25,937.85	26.8
Resolution	8,731.66	8.7	8,438.49	8.7
HMD Luminance	5,426.28	5.4	5,370.40	5.5
Ambient Luminance	3,490.26	3.5	3,332.30	3.4
HMD Accommodation Distance	3,290.56	3.3	4,214.71	4.3
Field of View	2,529.44	2.5	1.531.22	1.6
Contrast	1,445.87	1.4	1,254.38	1.3
Subjects	888.18	13.3	740.82	11.5
Error	246.48	10.3	157.63	6.8
Grand Mean	70.90		69.02	

the estimates. Thus, an average of the two scores in each condition was taken and this average score was used in the final analysis for each criterion measure.

HMD Visibility

Table 5 shows the analysis of variance summary table for the HMD visibility criterion measure. Because of the large number of two-way interactions (58), only those significant beyond the 0.05 alpha level are shown.

Listed in order of proportion of variance accounted for (Eta squared), the following seven parameters were identified as having significant effects on HMD percent visibility:

Parameter	Percent Eta^2
Ambient Scene Complexity	26.3
Resolution	9.0
HMD Luminance	5.6

TABLE 5. ANALYSIS OF VARIANCE SUMMARY: HMD PERCENT VISIBILITY

Source		Sums of Squares	Degrees of Freedom	Means Squares	F-Ratio	Significance Level	Percent Eta^2
Contrast	(A)	1350.70	1	1350.70	7.19	<0.01	1.4
Ambient Scene Luminance	(B)	3407.22	1	3407.22	18.14	<0.001	3.5
Ambient Scene Accommodation Distance	(C)	0.00	1	0.00	0.00	>0.25	0.0
Percent Transparency	(D)	213.73	1	213.73	1.14	>0.25	0.2
Resolution	(E)	8586.95	1	8536.95	45.70	<0.001	9.0
HMD Accommodation Distance	(F)	3741.07	1	3741.07	19.91	<0.001	3.9
Eye Dominance	(G)	157.53	1	157.53	0.84	>0.25	0.2
Color	(H)	88.50	1	88.50	0.47	>0.25	0.1
Framing	(J)	669.78	1	669.78	3.56	<0.10	0.7
Ambient Scene Complexity	(K)	25318.11	1	25318.11	134.76	<0.001	26.3
Field of View	(L)	2000.34	1	2000.34	10.65	<0.005	2.1
HMD Luminance	(M)	5405.44	1	5405.44	28.77	<0.001	5.6
AC		883.05	1	883.05	4.70	<0.05	0.9
AM		1738.97	1	1738.97	9.25	<0.005	1.8
BC		1378.13	1	1378.13	7.34	<0.01	1.4
BF		1411.18	1	1411.18	7.51	<0.01	1.5
BK		830.27	1	830.27	4.42	<0.05	0.9
BM		1618.80	1	1618.80	8.62	<0.01	1.7
CH		1258.76	1	1258.76	6.70	<0.05	1.3
CM		1182.14	1	1182.14	6.29	<0.05	1.2
DK		1059.14	1	1059.14	5.64	<0.05	1.1
FL		1683.38	1	1683.38	8.96	<0.01	1.8
GM		970.22	1	970.22	5.16	<0.05	1.0
HL		792.01	1	792.01	4.22	<0.05	0.8
KM		876.79	1	876.79	4.67	<0.05	0.9
Subjects		13492.08	15	899.47	4.79	<0.001	14.1
Error		7891.22	42	187.88	—	—	8.2
Total		96045.44	127				90.4

HMD Accommodation Distance	3.9
Ambient Scene Luminance	3.5
FOV	2.1
HMD Contrast	1.4
Total	51.8

The effects of ambient scene accommodation, HMD transparency, eye dominance, HMD color, and HMD framing were not significant. Significant main effects and interactions, plus subject effects, accounted for 38.2 percent of the total variance.

Figures 12 and 13 depict the parameter main effects. (Note that the graphs are truncated between zero and 40 percent.) It can be seen that ambient scene accommodation, HMD transparency, eye dominance, HMD color, and HMD framing had no effect on HMD visibility. With one exception, all significant main effects can be interpreted in terms of the relative contour strength of the two visual fields.

Ambient scene complexity had by far the largest single effect on HMD visibility. This was the expected outcome based on the binocular rivalry

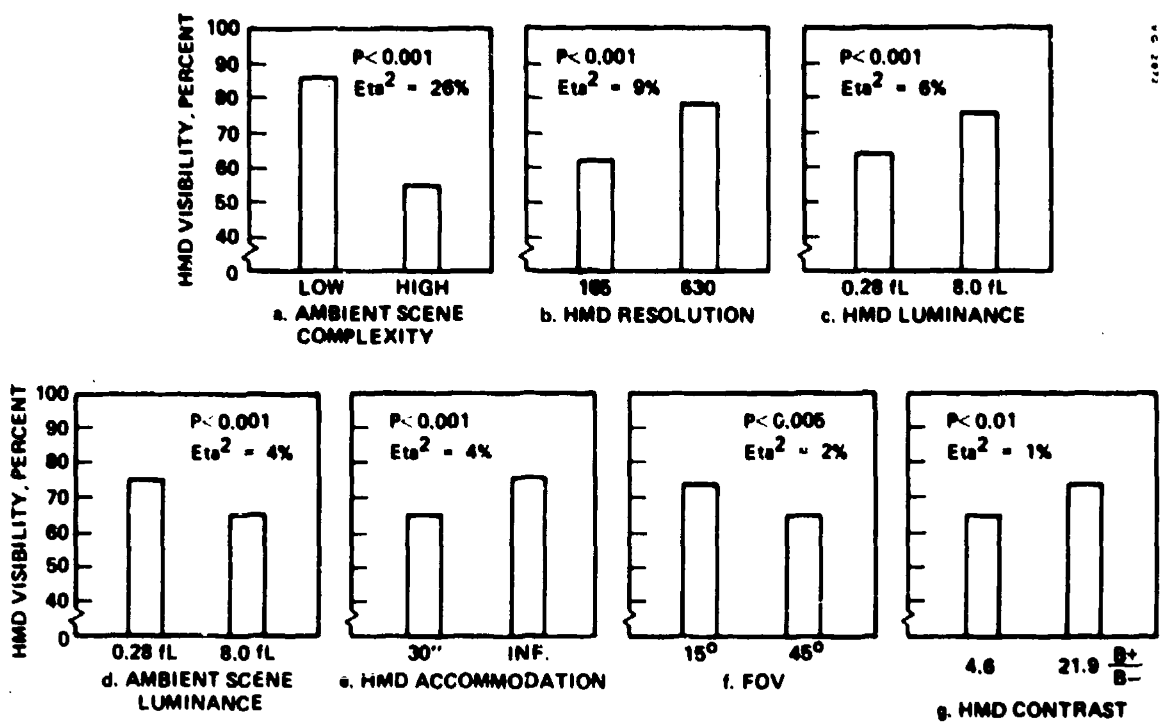


Figure 12. Results of screening study — HMD visibility, significant effects

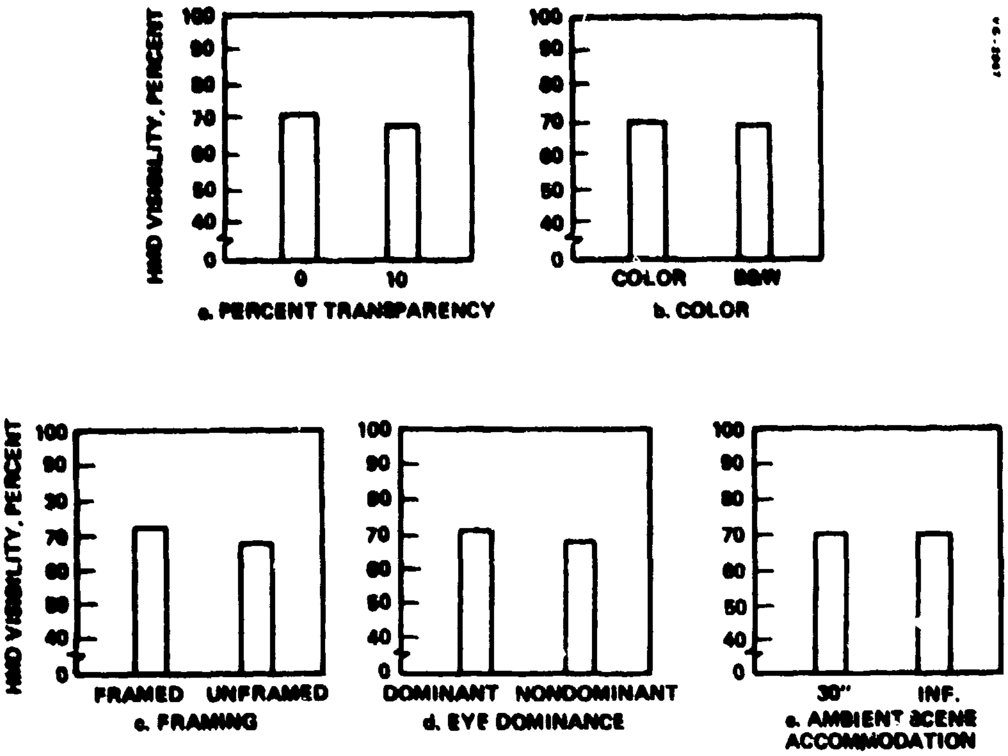


Figure 13. Results of screening study — HMD visibility, non-significant effects.

literature and pilot studies conducted prior to the screening study. Other contour strength related HMD parameters, such as resolution, contrast, and luminance play a secondary role to the relative number or amount of contours of the ambient scene. Because the contribution to the total variance of ambient scene complexity is so large, little or no information on other parameters of interest can be gathered if it is not controlled or systematically manipulated. In an actual flight situation, however, the relative difference in amount of contours of the two visual fields is not controlled and depends upon the particular image displayed on the HMD, and the visual scene viewed with the contralateral eye. The relative difference between the complexity of the two disparate fields can be constantly changing. It might be said that the amount of information which can be extracted from a given HMD system depends on where the pilot/operator is looking. Given a homogeneous field presented to the non-HMD eye, e.g., open sky, little or no rivalry will be experienced, provided, of course, relative luminance differences are not so great as to wash out the HMD. The more complex the ambient scene, the greater the amount of rivalry that will be experienced. Figure 12a shows that the low complexity ambient scene resulted in an average HMD visibility score of 84 percent compared with a score of 56 percent for the high complexity condition.

The second largest effect on HMD visibility was attributable to HMD resolution. Figure 12b indicates an increase of 16.4 percentage points at the 630-line resolution condition over the 165-line condition. Higher HMD resolution presumably increases the contour strength of the HMD image and increases its visibility, given a constant contralateral image.

Figure 12c shows that the HMD luminance condition of 8 fL resulted in a 13 percentage point increase in HMD visibility over the 0.28 fL condition. For a constant ambient scene luminance, increases in HMD luminance increased the contour strength of the HMD image resulting in higher visibility scores.

The significant main effect of HMD accommodation distance is puzzling. The infinity HMD accommodation condition produced significantly higher HMD visibility scores than did the 30-inch accommodation condition. It was not expected that the two levels of either HMD or ambient scene accommodation would differentially effect HMD visibility. The expected outcome was that HMD visibility might be influenced when the accommodation distances between the two scenes were different but not when they were the same. In other words, a significant interaction effect was expected between HMD and ambient scene accommodation, but neither main effect was expected to be significant. Figures 12e and 13e show the mean scores for the 30-inch and infinity accommodation distances for HMD and ambient scenes, respectively. The average HMD scene visibility scores for the two levels of ambient scene accommodation distance are identical, according to expectation. The significant effect of HMD accommodation may have resulted from some equipment artifact; although, the source of the artifact is not immediately apparent. A possible explanation is that at the infinity accommodation condition, the projector screen was actually closer (15.5 inches) to the subject's eye than at the 30-inch condition. The increase in visual acuity resulting from the closer eye-to-screen distance might account for the higher HMD visibility scores for the HMD accommodation parameter, but this does not explain why the same effect did not obtain for the ambient scene accommodation parameter.

Ambient scene luminance had an inverse effect on HMD visibility scores as shown in Figure 12d. Increases in ambient scene luminance increase the contour strength of the ambient scene image relative to that of the HMD image, which consequently results in low HMD visibility scores.

The 15-degree HMD field of view produced significantly higher HMD visibility scores than the 45 degree condition. Comparison of the mean scores is shown in Figure 12f.

As previously mentioned, the contour strength of the retinal image of the open eye will depend upon where the operator is looking. However, for a given contour strength of the non-HMD retinal image, changes in HMD FOV (for a fixed HMD scene) result in a change of relative contour strength between the two disparate images. That is, for two disparate retinal images of given contour strengths, decreases in HMD FOV will increase the contour strength of the HMD image relative to that of the non-HMD image. This increase in

HMD image contour strength will increase the predominance (or visibility) of the HMD image. This is not to say, however, that smaller FOVs should be recommended to increase HMD visibility, since the contour strength of both images is continually changing in a real world situation. FOV design recommendations must be made relative to such consideration as sensor type, sensor FOV, target size, mission, and pilot task.

The differences in binocular rivalry found in this study as a function of HMD FOV are significant only in terms of the binocular rivalry phenomenon and must be related to operator performance data with real-world tasks. Smaller FOVs may aid the operator's ability to see a target displayed on his HMD, but unless the target size is sufficient for recognition nothing will have been gained by using a small FOV.

A comparison of the means of the two HMD contrast conditions is shown in Figure 12g. Average HMD visibility scores were significantly higher for the high contrast condition. The amount of variance accounted for by the contrast parameter, however, was only 1.4 percent. The range over which contrast was varied was not large. The high contrast condition was high only in a relative sense and was, in actuality, a normal photographic contrast. Low contrast transparencies were produced by washing out the normal contrast transparencies with ambient lighting, as mentioned earlier. A larger contrast effect probably would have been obtained had the range over which this parameter was varied been larger.

Thirteen two-factor interactions were found to be significant at or beyond the 0.05 significance level. The proportion of variance accounted for in all cases was less than 2 percent, which indicates that the effects are small. Additionally, it can be seen from Figure 14 that, taken separately, the slopes of the interaction curves are in the same direction for many of the interactions. This indicates that the interaction effects are spurious and could be removed by an appropriate transformation of the criterion scores. For those interactions where the curves were not in the same direction, the differences in slope were small. Moreover, even if transformation of the criterion scores could not remove the interaction, more than half the interaction effects are clearly spurious. For example, the ambient scene luminance by ambient scene accommodation interaction is not interpretable from theoretical or practical HMD system application considerations. It may be interpreted, however, upon consideration of the fact that, for face validity, two different scenes were used for the two ambient scene accommodation distances; a cockpit scene for the 30-inch distance and a ground scene for the infinity distance. The two transparencies differed considerably in average scene brightness even though the brightness of the area of HMD superimposition was controlled. If real, the interaction effect is most likely due to the two scenes rather than to accommodation distance.

A discussion of the interaction effects is not considered meaningful for the following reasons: 1) many of the interaction effects are spurious, 2) many of the interaction effects could be removed by transformation of the data, and 3) even if some of the interaction effects are real, the proportion of variance accounted for in each case is so small, any such effects are trivial.

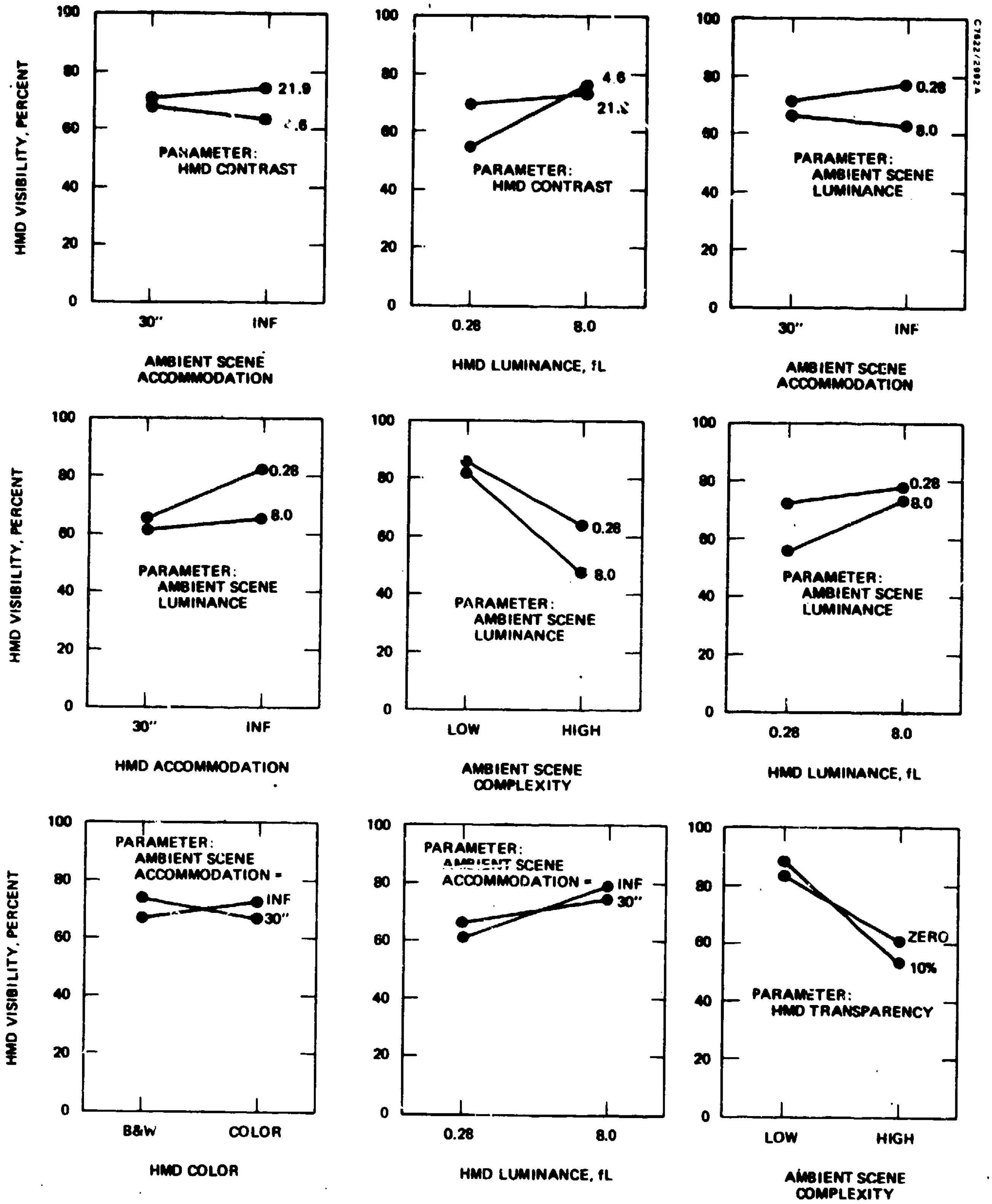


Figure 14. HMD visibility interaction effects.

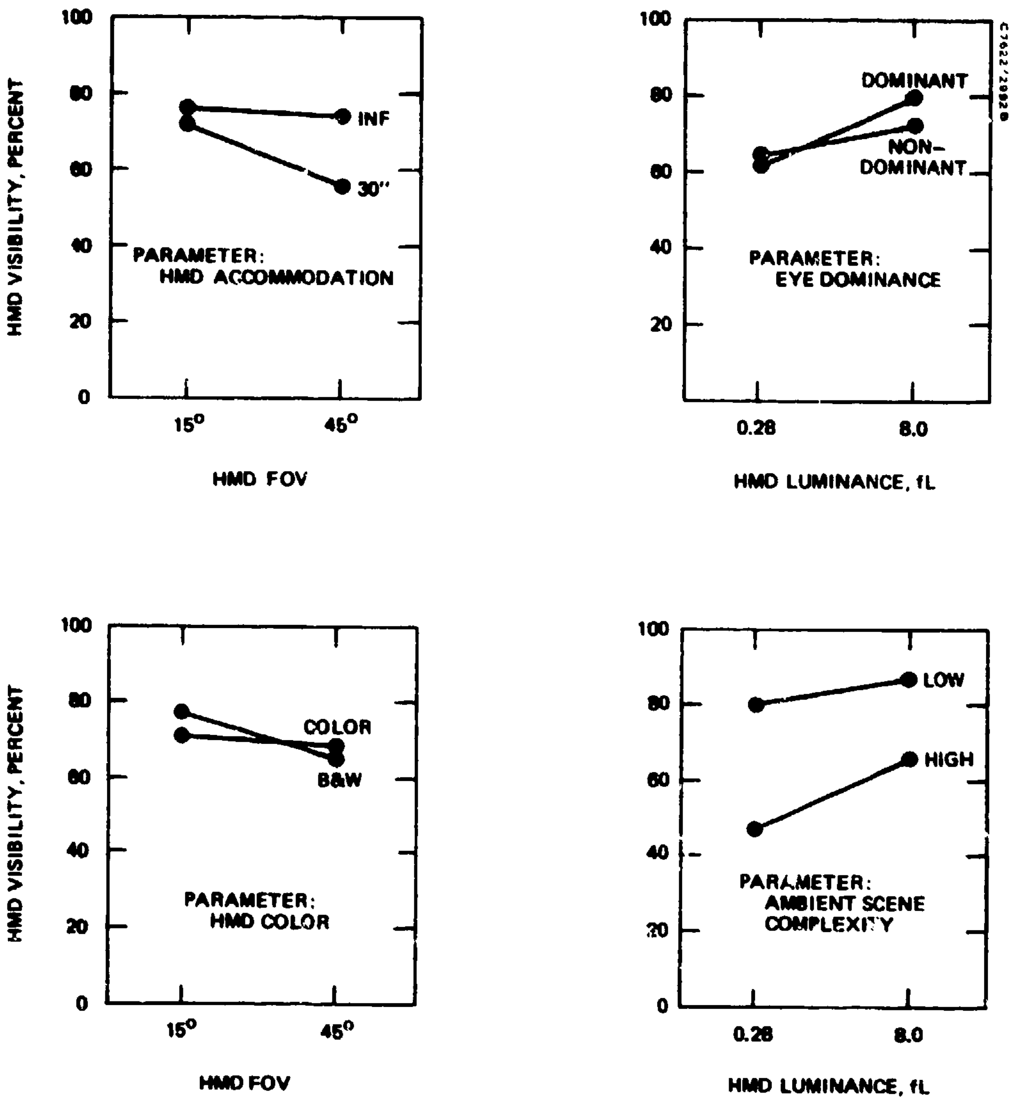


Figure 14. (Continued)

HMD Predominance

Table 6 shows the analysis of variance summary table for HMD image predominance. HMD predominance was defined as the percentage of the total viewing time during which this image was perceived at a visibility of 90 percent or more.

Listed in order of proportion of variance accounted for (Eta Squared), the following six parameters were identified as having significant main effects on HMD predominance scores:

Parameter	Percent Eta^2
Ambient Scene Complexity	23.9
HMD Resolution	14.9
HMD Field of View	2.9
HMD Accommodation Distance	2.4
HMD Contrast	1.7
HMD Luminance	1.4

The effects of ambient scene luminance, ambient scene accommodation distance, percent transparency, eye dominance, color, and framing were not significant. Significant main effects and interactions, plus subject effects, accounted for 74.3 percent of the total variance. Figure 15 shows the main effects for HMD predominance.

The results of the HMD predominance measure are essentially the same as the HMD visibility criterion measure, with the exception of the two luminance parameters. HMD luminance accounted for only 1.4 percent of the variance with the HMD predominance measure compared with 5.6 percent for HMD visibility. While ambient scene luminance accounted for 3.5 percent of the total variance of HMD visibility, it failed to achieve statistical significance for this measure. This lack of significance can be explained by the larger error term for HMD predominance, which was 10.3 percent of the total variance compared with 8.2 percent for HMD visibility. If an error term for HMD predominance is calculated at 8.2 percent of the total variance, the ambient scene luminance parameter attains significance at the 0.05 alpha level.

Ten of the 58 two-factor interactions reached significance at the 0.05 alpha level, however, many are considered to be spurious, due to the measurement scale, and in any case, the effects are trivial, accounting for less than 2 percent of the total variance in each instance. The interaction effects are shown in Figure 16.

TABLE 6. ANALYSIS OF VARIANCE SUMMARY: HMD PREDOMINANCE

Source		Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Significance Level	Percent Eta^2
Contrast	(A)	975.72	1	975.72	6.85	<0.05	1.7
Ambient Scene Luminance	(B)	536.28	1	536.28	3.76	<0.10	0.9
Ambient Scene Accommodation Distance	(C)	0.98	1	0.98	0.01	>0.25	0.0
Percent Transparency	(D)	15.54	1	15.54	0.11	>0.25	0.0
Resolution	(E)	8659.11	1	8659.11	60.83	<0.001	14.89
HMD Accommodation Distance	(F)	1371.55	1	1371.55	9.64	<0.005	2.36
Eye Dominance	(G)	288.60	1	288.60	2.03	>0.10	0.0
Color	(H)	5.71	1	5.71	0.04	>0.25	0.0
Framing	(J)	533.84	1	533.84	3.75	<0.10	0.9
Ambient Scene Complexity	(K)	13894.45	1	13894.45	97.61	<0.001	23.89
Field of View	(L)	1695.07	1	1695.07	11.91	<0.005	2.91
HMD Luminance	(M)	819.13	1	819.13	5.75	<0.05	1.41
AC		842.55	1	842.55	5.92	<0.05	1.45
AG		951.57	1	951.57	6.69	<0.05	1.64
AM		606.44	1	606.44	4.26	<0.05	1.04
BC		659.76	1	659.76	4.64	<0.05	1.13
BE		897.92	1	897.92	6.31	<0.05	1.54
BF		653.43	1	653.43	4.59	<0.05	1.12
CF		586.55	1	586.55	4.12	<0.05	1.01
CK		785.10	1	785.10	5.52	<0.05	1.35
CL		623.09	1	623.09	4.38	<0.05	1.07
GM		929.90	1	929.90	6.63	<0.05	1.60
Subjects		8255.62	15	550.37	3.87	<0.001	14.20
Error		5978.35	42	142.34	-	-	10.28
	Total	58150.02	127				84.57

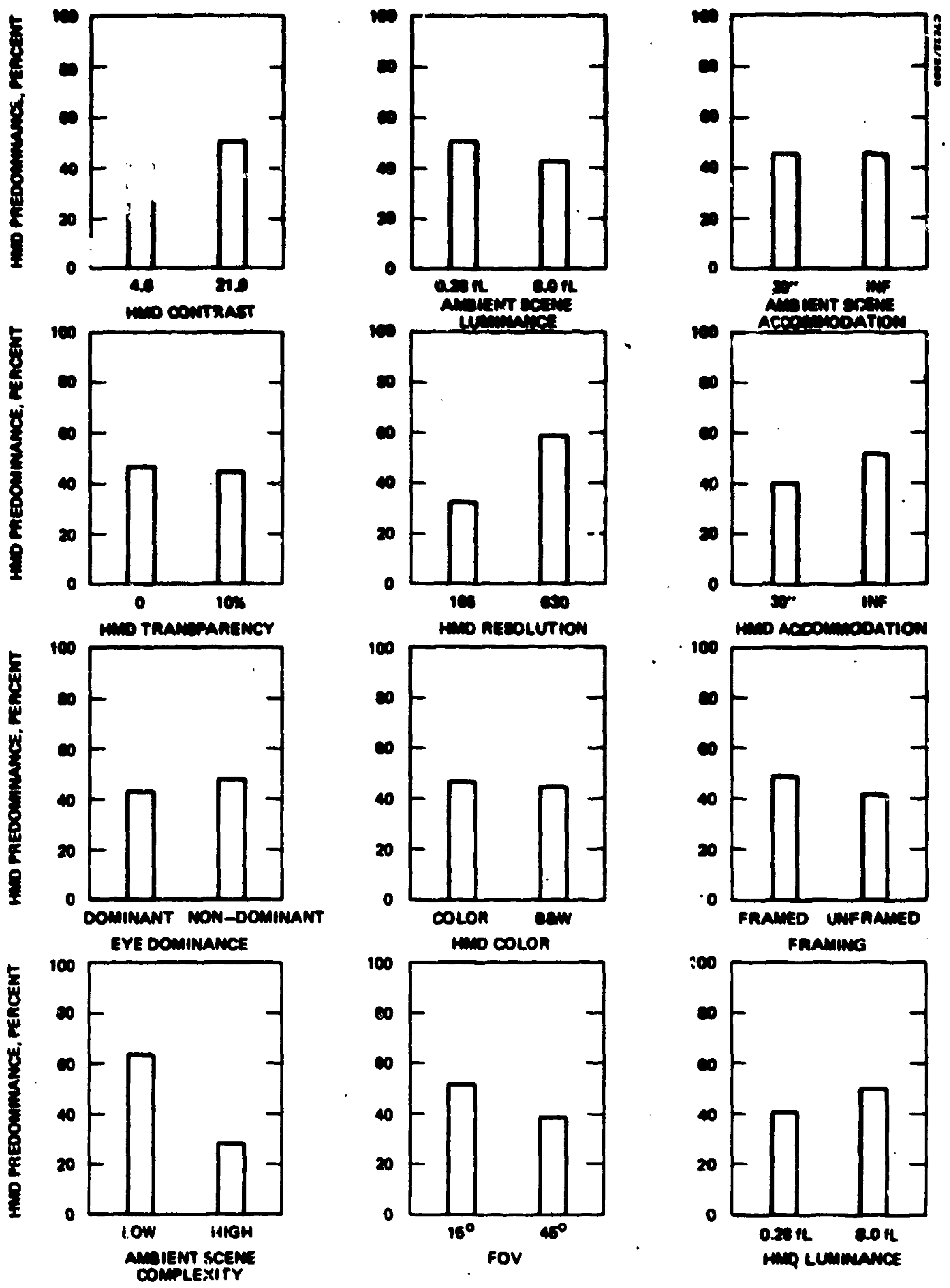


Figure 15. Results of screening study — HMD predominance, percent.

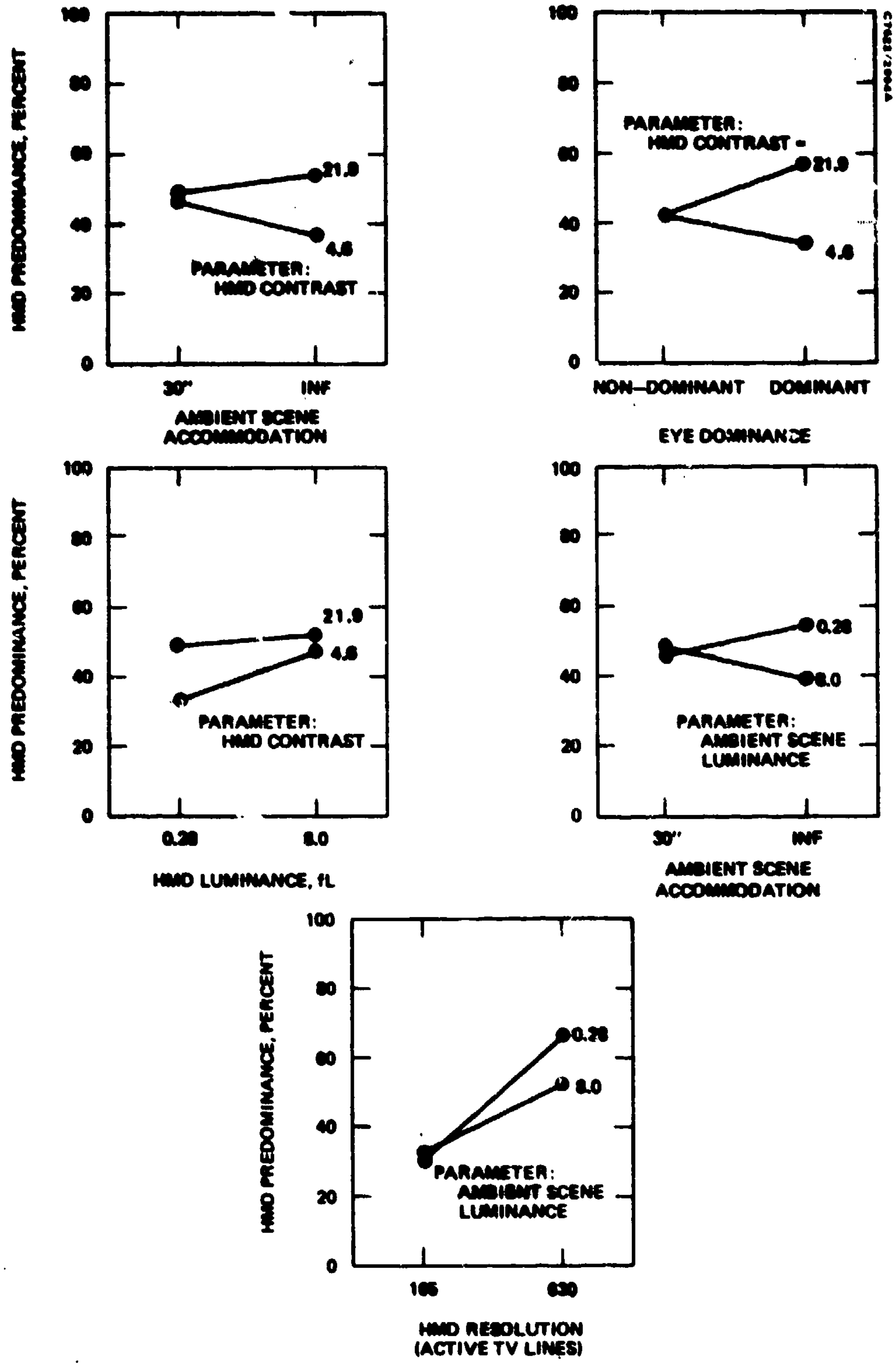


Figure 16. HMD predominance interaction effects.

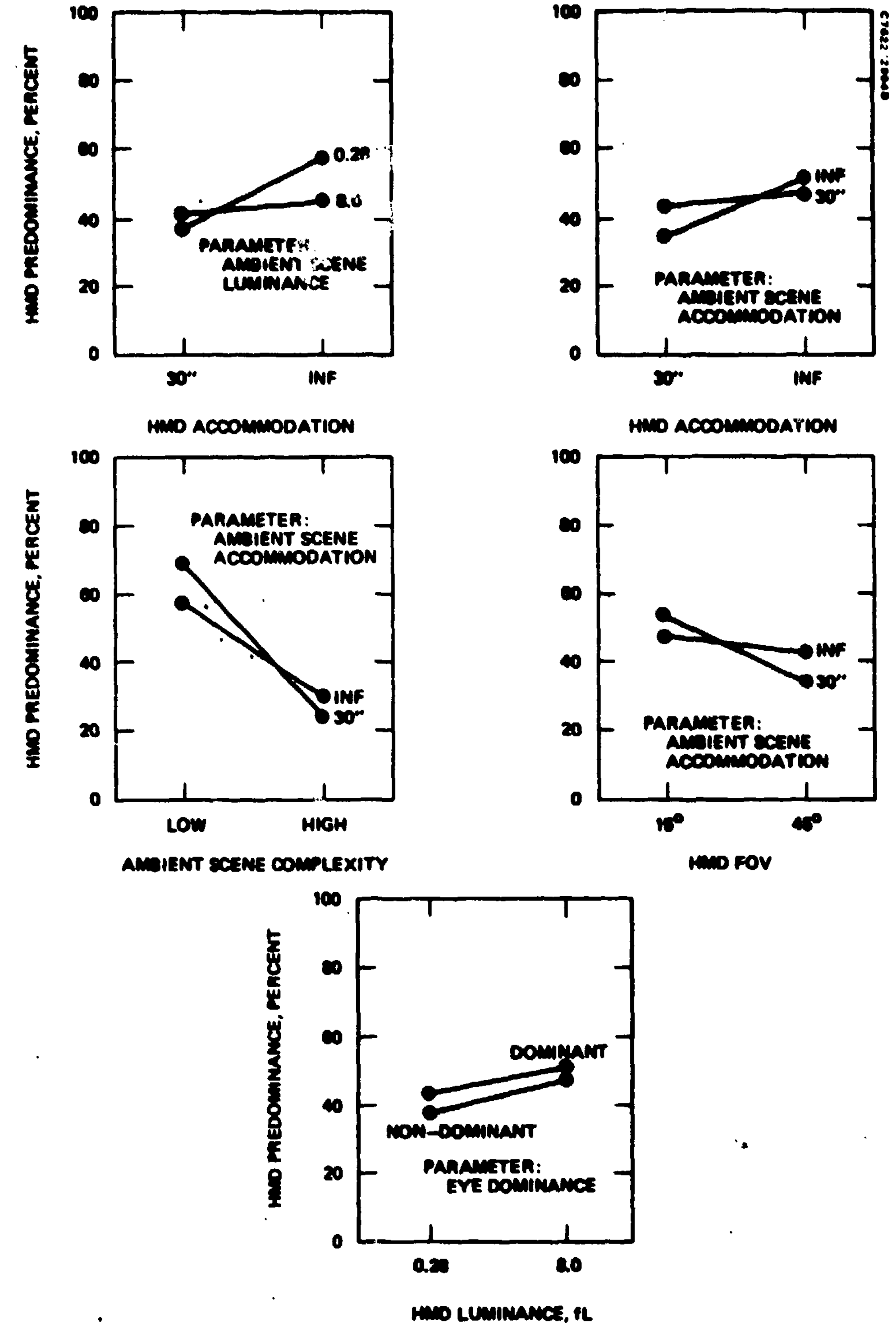


Figure 16. (Continued).

Ambient Scene Predominance

Table 7 shows the analysis of variance summary table for ambient scene predominance, i.e., the percentage of total viewing time during which the ambient scene was perceived at a visibility of 90 percent or more.

Listed in order of proportion of variance accounted for (Eta^2), the following four parameters were identified as having significant main effects on ambient scene predominance:

Parameter	Percent Eta^2
Ambient Scene Complexity	17.4
HMD Luminance	8.9
HMD Resolution	4.5
Ambient Scene Luminance	4.0

The effects of HMD contrast, ambient scene accommodation distance, HMD transparency, HMD accommodation distance, eye dominance, color, framing, and FOV were not significant. Main effects and interactions, plus subject effects, accounted for 78.1 percent of the total variance. Figure 17 shows the main effects for ambient scene predominance. Ambient scene predominance scores were inversly related to HMD visibility and HMD predominance scores. For example, ambient scene complexity, which had the largest single effect, had higher ambient scene predominance scores associated with the high complexity condition while the reverse was true for HMD visibility and predominance scores. This is, of course, the expected outcome.

The four significant interaction effects are shown in Figure 18. The proportion of variance accounted for by three of the interactions indicates that the statistical relationship is moderately strong. The slopes of the curves, however, indicate that the interaction effects, while not trivial, could be removed by an appropriate transformation of the raw scores.

While the statistical analyses are in essential agreement, a discrepancy exists between the results of the three criterion measures. The two luminance parameters, which had significant effects on HMD visibility, had little or no effect on HMD predominance, but were highly significant for ambient scene predominance. This difference between the two predominance measures was not expected and raises the question of the appropriateness of the response measures. The predominance scores were recorded primarily as a measure of the alternation cycle during rivalry. It was felt that identical average visibility scores could result from various combinations of control lever input. For example, an average HMD visibility score of 50 percent could result from moving the response lever full forward (100 percent) for 30 seconds, then full back (zero percent) for 30 seconds, or from leaving the

TABLE 7. ANALYSIS OF VARIANCE SUMMARY: AMBIENT SCENE PREDOMINANCE

Source		Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Significance Level	Percent Eta^2
Contrast	(A)	317.20	1	317.20	3.02	<0.10	1.2
Ambient Scene Luminance	(B)	1004.88	1	1004.08	9.54	<0.005	4.0
Ambient Scene Accommodation Distance	(C)	37.95	1	37.95	0.36	>0.25	0.1
Percent Transparency	(D)	74.88	1	74.88	0.71	>0.25	0.3
Resolution	(E)	1133.46	1	1133.46	10.78	>0.005	4.5
HMD Accommodation Distance	(F)	395.86	1	395.86	3.76	<0.10	1.6
Eye Dominance	(G)	19.29	1	19.29	0.18	<0.25	0.1
Color	(H)	99.31	1	99.31	0.94	>0.25	0.4
Framing	(J)	122.27	1	122.27	1.16	>0.25	0.5
Ambient Scene Complexity	(K)	4430.93	1	4430.93	42.12	<0.001	17.4
Field of View	(L)	282.33	1	282.33	2.68	<0.25	1.1
HMD Luminance	(M)	2272.22	1	2272.22	21.60	<0.001	8.9
BC		438.45	1	438.45	4.17	<0.05	1.7
BM		853.36	1	853.36	8.11	<0.01	3.4
CM		711.12	1	711.12	6.76	<0.025	2.8
KM		805.51	1	805.51	7.66	<0.01	3.2
Subjects		3749.93	15	250.00	2.38	<0.025	14.8
Error		4418.03	42	105.19	-	-	17.4
	Total	25410.56	127				78.1

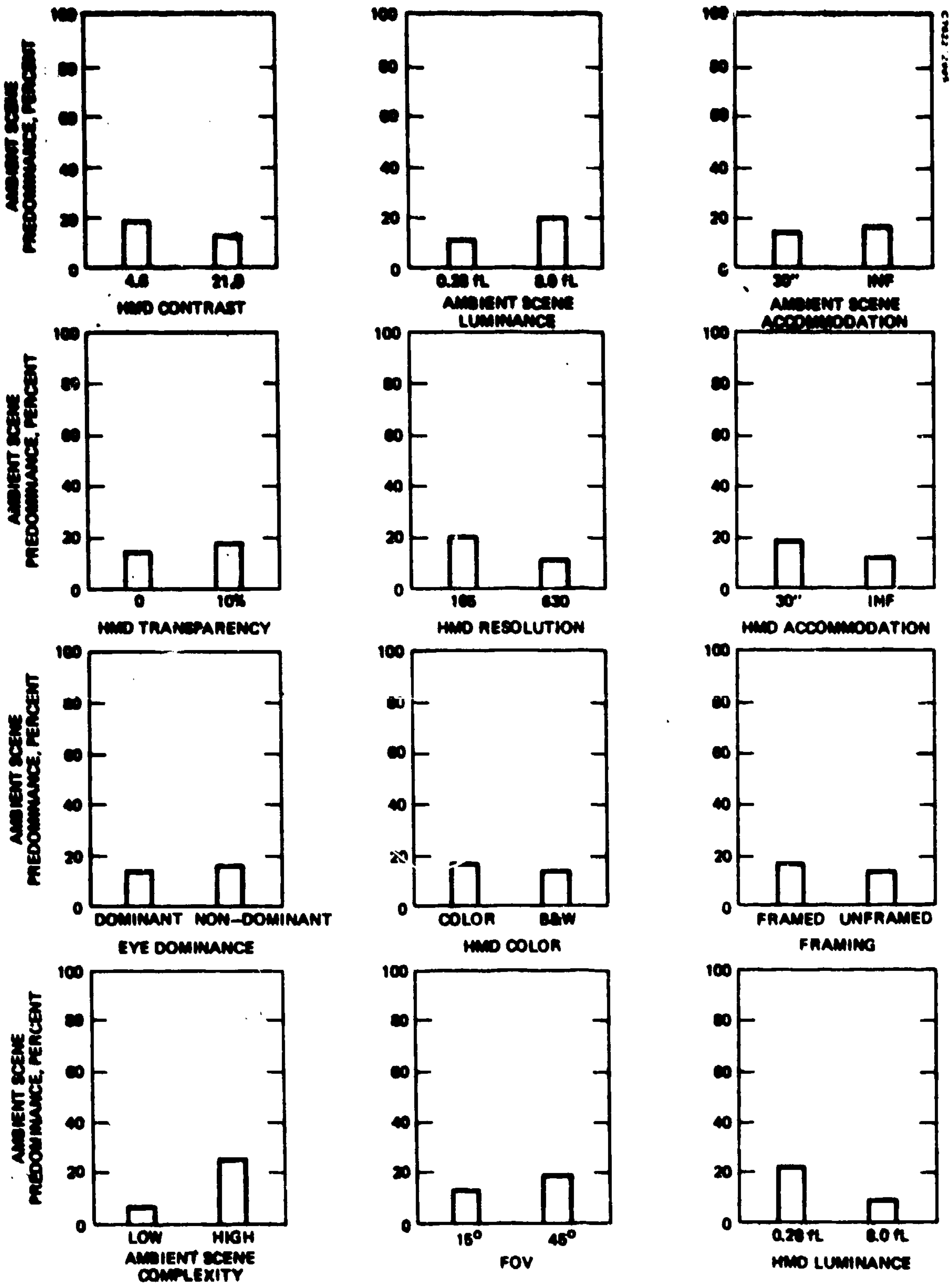


Figure 17. Results of screening study – HMD predominance, percent

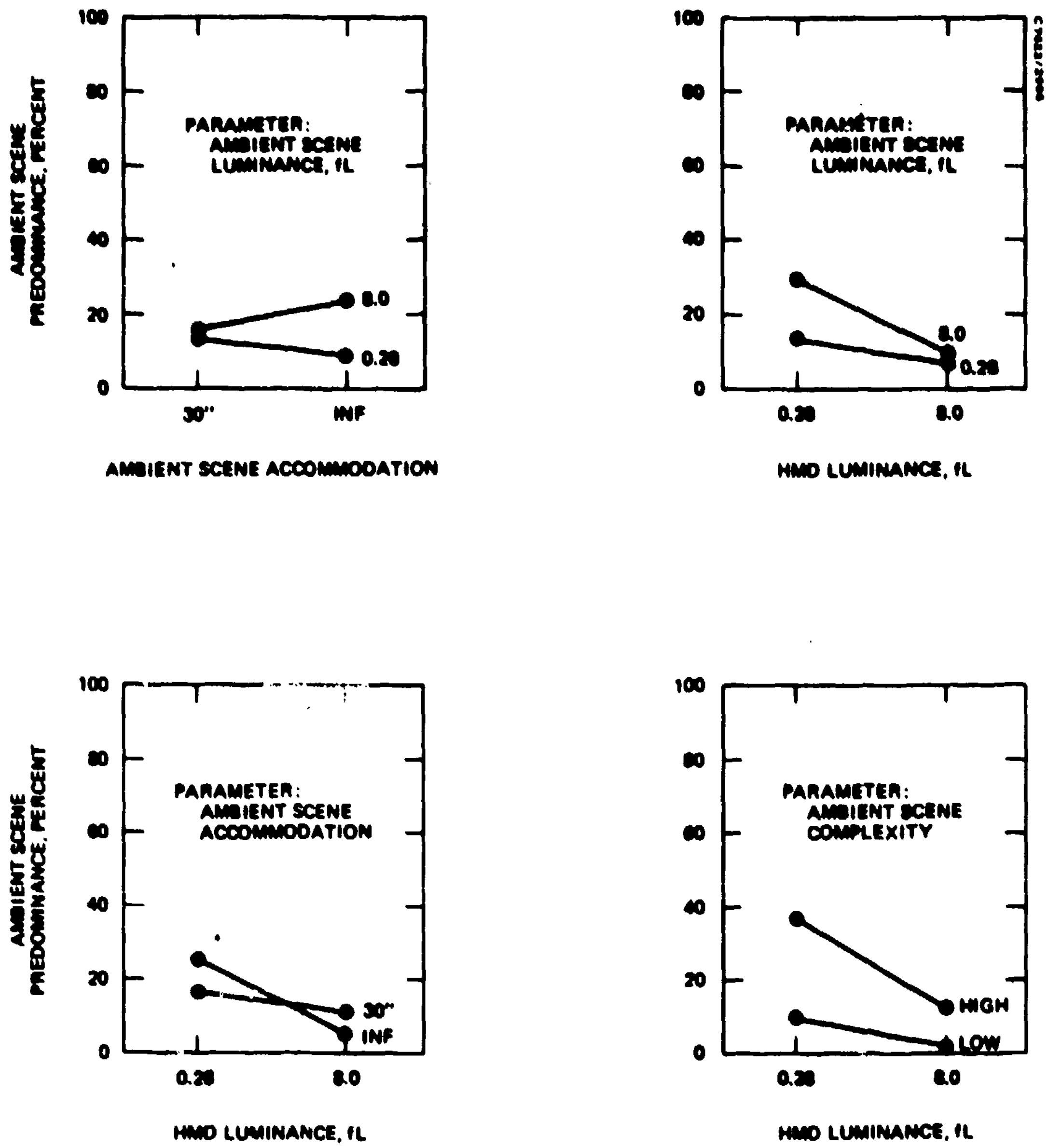


Figure 18. Ambient scene predominance interaction effects.

response lever at the 50 percent visibility position for 60 seconds. The combinations resulting in the same score are infinite. It was judged that by collecting predominance scores, it would be possible to distinguish between different alternation cycles. It was observed during the experiment, however, that subject response patterns were consistent and showed the expected alternation of the two visual fields. From a consideration of the error terms in the three analyses (8.2, 10.3, and 17.4 percent Eta^2 for HMD visibility, HMD predominance, and ambient scene predominance respectively), the HMD visibility scores appear to be the most reliable. Taken together, the predominance measures, because of their discrepant results and larger error variance, are not considered as valid a measure of binocular rivalry as is the HMD visibility measure for this study.

The greater variability of predominance measures may be attributed to intervening processes, such as response bias or perceptual set, to which the predominance measures were more sensitive than the visibility measure, because the former were activated only at the extreme ends of the control lever stroke. There is evidence from the data to indicate that intervening processes may have influenced the measures of binocular rivalry.

The overall grand mean for HMD visibility was 70 percent. Since the average quality of the HMD imagery was inferior to that of the ambient scene imagery due to resolution values (assuming no large difference in amount of contour per area), the grand mean value was expected to be less than 50 percent. Since it cannot be assumed that an isomorphic relationship exists between perception in rivalry and response device input, it is not clear whether the HMD visibility grand mean represents the average perceptual response or whether it has been influenced by an intervening process. Caution is necessary in categorizing an effect as perceptual when it may be something else. The problem arises because the investigation of perceptual phenomena, such as binocular rivalry, cannot make use of direct observation of the process.

The grand means of the predominance scores also indicate the possible influence of intervening variables. According to the alternation model, pure oscillation between the two visual fields should result in an overall mean of 30 seconds or 50 percent for each field, provided the stimulus strength of the two images was equal. Alternation is not complete, however, and a transition stage is experienced where portions of each image are perceived. Thus, the predominance score for either image was expected to be less than 50 percent. Furthermore, the average quality of the HMD images was inferior to that of the ambient scene images due to the resolution and contrast values. Consequently, HMD predominance was expected to be less than ambient scene predominance, based on image related parameters. The respective HMD and ambient scene predominance grand mean scores of 45.3 and 15 percent are not according to expectation and suggest either greater contour strength in the HMD imagery or the influence of intervening processes. Since there was no a priori reason to suspect inherent contour strength differences between HMD and ambient scene imagery, the grand means of the criterion measures, which are biased in favor of the HMD scene, are probably best interpreted in terms of intervening processes.

Two intervening processes suggest themselves as possibly biasing HMD visibility and predominance scores. The first is response bias. It is possible that subjects tended to favor moving the response lever forward rather than backward (for anthropometric or other considerations), thus influencing the grand means in the direction of higher HMD visibility and predominance scores and lower ambient scene predominance scores. A method of controlling for response bias is to alternate the direction of response device movement associated with each visual field in a balanced fashion so that for each subject, on half the trials increased HMD visibility would be indicated by forward movement of the response device, and on half the trials by backward movement of the control lever. This method of controlling for response bias was considered, but was rejected since it was deemed that changing the direction of movement representing a particular scene would only confuse the subjects on an already difficult task. Moreover, since the response device was spring loaded and came to rest at an easily discernable 50 percent HMD visibility position, it is not felt that the effect of response bias, if any, was large.

The second intervening process, perceptual set, is considered a more likely candidate for influencing scores in a direction favorable to the HMD scene. The effect of set in perception is well documented. The general principle is that the individual is "prepared" implicitly or explicitly, for a certain stimulus input. The input is actively dealt with on the basis of this preparation. The perceived input is at least partly dependent on the nature of the preparation. One way to provide perceptual set is through instructions. In the present study, subjects were asked to judge the visibility of the helicopter in the HMD scene, but to make no effort to see the helicopter. It was necessary to select a "target" image for evaluation of rivalry since not to do so was too confusing a task due to image complexity. Instructional emphasis on the HMD image, then, may have induced a set to see this image even though subjects were asked to make no effort to see either image. These latter instructions were given on the basis of reports from Hughes engineers and pilots experienced with HMD systems that some individuals, with proper concentration, can see either image at will. Others are able to learn to do this with training. It was mentioned earlier that the data from one subject was discarded because of his ability to see either image on demand. It is suggested that further research on binocular rivalry in HMD systems explore psychological variables such as perceptual set, training, and attention and physiological variables such as fatigue to determine their effects on perception in rivalry in general and their influence on operator performance using real-world tasks with HMD systems specifically.

Conclusions

The following seven parameters were identified as having statistically significant effects on binocular rivalry as measured by percent visibility of the HMD target image: 1) ambient scene complexity, 2) HMD resolution, 3) HMD luminance, 4) HMD accommodation distance, 5) ambient scene luminance, 6) HMD field-of-view, and 7) HMD contrast. With the exception of HMD accommodation distance, all significant main effects were interpreted on the basis of relative image contour strength. It was concluded that the higher HMD visibility scores associated with the infinity condition of HMD accommodation may have been an artifact of the apparatus and/or imagery used for this study. In any case, since the HMD design trend is toward an infinity HMD accommodation, the results were accepted as valid, and the HMD simulation apparatus was set up for infinity accommodation for the subsequent parametric study.

Although 13 of the 58 measurable two-factor interactions showed statistical significance, it was concluded that the strength of association was trivial based on the large sample size and, thus, an interpretation of these interactions was not pursued.

Because of some discrepancies in the data and relatively large error variances, it was concluded that the HMD and ambient scene predominance criterion measures were not appropriate measures of binocular rivalry for this study. The discrepancies in the data were interpreted as attributable to intervening processes rather than as an elucidation of the basic visual mechanism under investigation. It was concluded that the predominance measures were more sensitive to the intervening processes than was the HMD visibility measure, and for this reason the former were not used in subsequent studies.

As mentioned above, it was decided to control HMD accommodation distance at infinity for the parametric study ratner than explore it parametrically. Similarly, since ambient scene complexity is not a design consideration, it was concluded that this parameter should be controlled (because of its very large contribution to criterion score variance) rather than examined at various levels. Although the contribution of HMD contrast to the total variance was small (1.4 percent), this parameter was considered to be important in binocular rivalry related to HMD display design and should be examined with a larger range of values.

PARAMETRIC STUDY

Purpose

The parametric study was conducted to determine the functional relationships between binocular rivalry and those parameters identified from the screening study as having important effects on binocular rivalry with HMDs. Based on the results of the screening study, five parameters were selected for investigation in the parametric study. These parameters were HMD resolution, HMD target contrast, HMD luminance, ambient scene luminance, and HMD field of view.

Imagery

New HMD imagery was required to expand the range of resolution and contrast levels. To better control contrast values, HMD imagery was photographed under controlled conditions. A model M60 tank was photographed against a plain white background on high and normal contrast film.

Since the screening study showed that ambient scene accommodation distance did not effect HMD visibility scores, this parameter was fixed at infinity and a ground scene was used for the ambient scene. Figure 19 shows the ground scene used.

Operational Definitions of Study Parameters

Table 8 shows the values of each of the five parameters examined in the parametric study.

Table 9 shows the values at which the remaining seven parameters were fixed.

Operational definitions of all the parameters were the same as in the screening study. Figure 20 shows the parametric study HMD tank images for the nine resolution and contrast conditions.

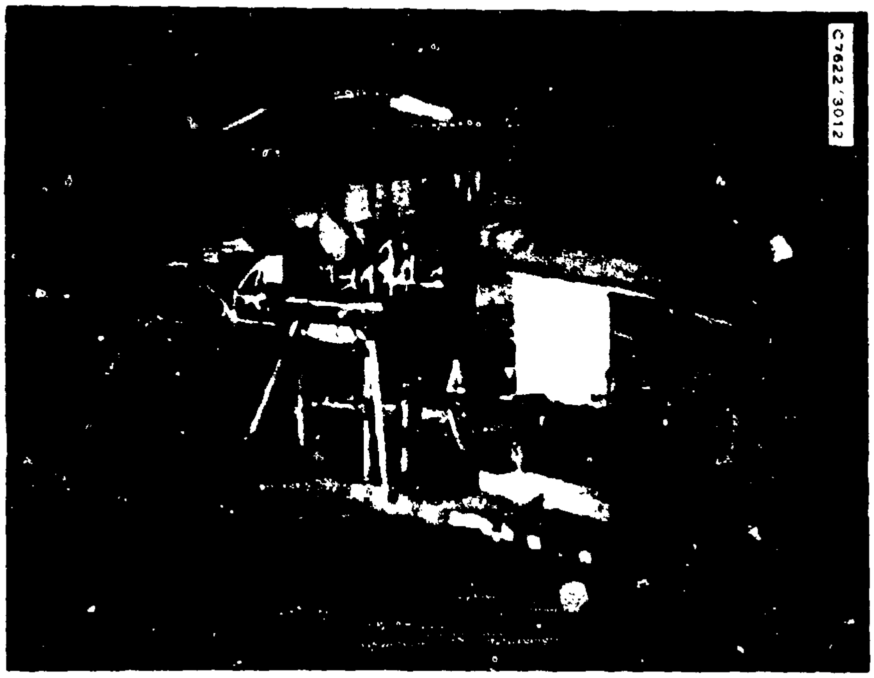


Figure 19. Ambient scene used in parametric study.

TABLE 8. PARAMETERS AND PARAMETER LEVELS FOR PARAMETRIC STUDY

Parameters	Parameter Values
Resolution	263, 525, and 875 TV lines
Contrast	2.2:1, 4.8:1, and 24.3:1 $\left(\frac{B_{max}}{B_{min}}\right)$
Average HMD luminance	0.28, 8.0, and 80 fL
Average ambient scene luminance	0.28, 8.0, and 80 fL
Field of view	15, 30, and 45 degrees

TABLE 9. FIXED VALUES OF PARAMETERS NOT PARAMETRICALLY EXAMINED

Parameter	Fixed Value
HMD accommodation distance	Infinity
Ambient scene accommodation distance	Infinity
Eye presentation	Left Eye
Framing	Unframed
Color/monochrome	Black and White
Transparency	0.05 percent
Ambient scene complexity	High

Dependent Measure

The dependent (performance) measure for the parametric study was HMD visibility as defined for the screening study.

Subjects Task

The subject's task was the same as described in the screening study.

Research Design

To establish functional relationships between HMD parameters and binocular rivalry, it is necessary to examine each parameter at three or more levels. As five parameters were selected for investigation, a complete factorial study at three levels would require 243 data points for a single replication. Since the screening study showed that intersubject differences are large (accounting for better than 14 percent of the total variance) and because of the large sample size required, between-subject designs were to be avoided.

A complete factorial within-subjects design would require 243 observations per subject. It was not considered reasonable to submit subjects to such an extended number of trials. Therefore, it was necessary to select a within-subjects design with reduced block size. Additionally, the existence of carry-over effects (e. g. learning with time on task) in binocular rivalry was to be avoided. Consequently, it was considered necessary to keep the number of trials per subject small to minimize such effects.

Three within-subjects design alternatives were considered to reduce the block size: 1) several smaller experiments, 2) a central-composite design, and 3) a fractional factorial of the full 3^5.

The small studies considered were 3^2 and 3^3 complete factorials. The first presented no problems, but the second still required 27 observations per subject, which was considered too large. There was no way to reduce block size, since neither an incomplete blocks or Youden square design (to use ambient scene complexity as a second blocking dimension) exists for 27 treatments. This approach was therefore rejected.

The central-composite design posed the same problem. Even though the total number of observations was reduced, the number of trials required per subject was considered too large. Moreover, central-composite designs require specified, preselected values of parameter levels. Since it was not practical to achieve these values for all parameters (e. g. , contrast), this design approach was also rejected.

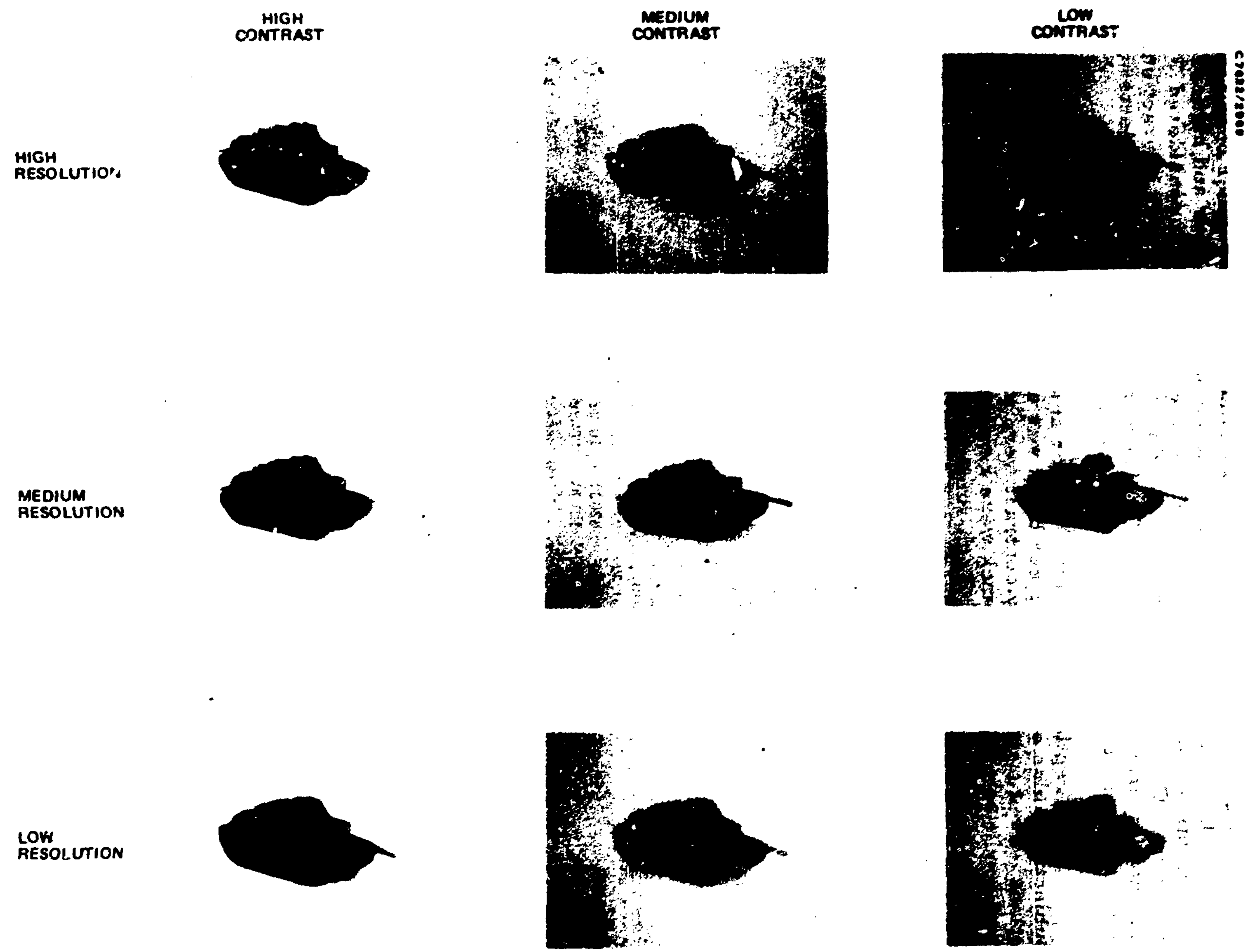


Figure 20. Example of resolution and contrast conditions for parametric study.

A fractional replication of the complete factorial offered the advantages of reducing both the size of the whole experiment and the number of trials per subject. With this approach, information on three-factor and higher interactions is sacrificed; however, these interactions were considered negligible. The screening study indicated that even two-factor interactions were not important. Therefore, a fractional replication within subjects design was selected for the parametric study.

A 1/3 replication of a full 3^5 factorial design arranged in nine blocks (subjects) of nine observations per block was used. All two-factor interactions except field of view by contrast were measurable. The nine treatment conditions within each block were randomized, and subjects were randomly assigned to blocks. Each subject was measured twice under each condition, and an average of the two measurements was used for data analysis. The design model is shown in Table 10.

TABLE 10. DESIGN MODEL FOR PARAMETRIC STUDY

Blocks								
1	2	3	4	5	6	7	8	9
00000	22002	11001	22200	11202	00201	11100	00102	22101
10101	02100	21102	02001	21000	10002	21201	10200	02202
20202	12201	01200	12102	01101	20100	01002	20001	12000
22110	11112	00111	11010	00012	22011	00210	22212	11211
02211	21210	10212	21111	10110	02112	10011	02010	21012
12012	01011	20010	01212	20211	12210	20112	12111	01110
11220	00222	22221	00120	22122	11121	22020	11022	00021
21021	10020	02022	10221	02220	21222	02121	21120	10122
01122	20121	12120	20022	12021	01020	12222	01221	20220

Subjects

Nine of the Hughes engineers used in the screening study were randomly selected to serve as subjects.

Apparatus

The experimental apparatus, as described for the screening study, was used without modification.

Procedure

Subjects were brought into the laboratory, seated at the apparatus, and given a copy of the experiment instructions. The instructions are presented in Appendix B of this report. Experimental procedure was the same as that used for the screening study with the exception that the HMD image was the tank rather than the helicopter used in the screening study. Also predominance scores for the two visual fields were not taken for the reasons outlined in the discussion of the screening study results.

Results and Discussion

Table 11 shows the analysis of variance summary for the parametric data.

TABLE 11. ANALYSIS OF VARIANCE SUMMARY: PARAMETRIC STUDY, HMD PERCENT VISIBILITY

Source	Sums of Squares	Degrees of Freedom	Mean Square	F-Rate	Significance Level	Percent Eta Squared
Resolution (A)	778.6	2	389.3	1.89	<0.25	0.6
Contrast (B)	2884.4	2	1442.2	7.00	<0.005	6.0
HMD luminance (C)	15876.7	2	7938.3	38.52	<0.001	32.0
Field of view (D)	117.5	2	58.8	0.29	>0.25	0.2
Ambient scene luminance (E)	12984.5	2	6492.3	31.50	<0.001	26.0
AB	801.2	4	200.3	0.97	>0.25	1.6
AC	650.7	4	162.7	0.79	>0.25	1.3
AD	1147.8	4	287.0	1.39	>0.25	2.3
AE	830.4	4	207.6	1.01	>0.25	1.7
BC	212.6	4	53.2	0.26	>0.25	0.4
BE	75.5	4	18.9	0.09	>0.25	0.2
CD	655.0	4	163.8	0.79	>0.25	1.3
CE	959.3	4	239.8	1.16	>0.25	1.9
DE	429.1	4	107.3	0.52	>0.25	0.9
Subjects	5599.9	8	700.0	3.40	<0.05	11.0
Error	4946.6	24	206.1	—	—	9.0
Total	50125.4	80				

HMD contrast, HMD luminance, and ambient scene luminance had significant effects on HMD visibility, while HMD resolution and FOV did not. None of the two-factor interactions was significant at the 0.05 alpha level. Significant main effects and the effects of subjects accounted for 75 percent of the total variance. Figure 21 illustrates the main effects of the five parameters.

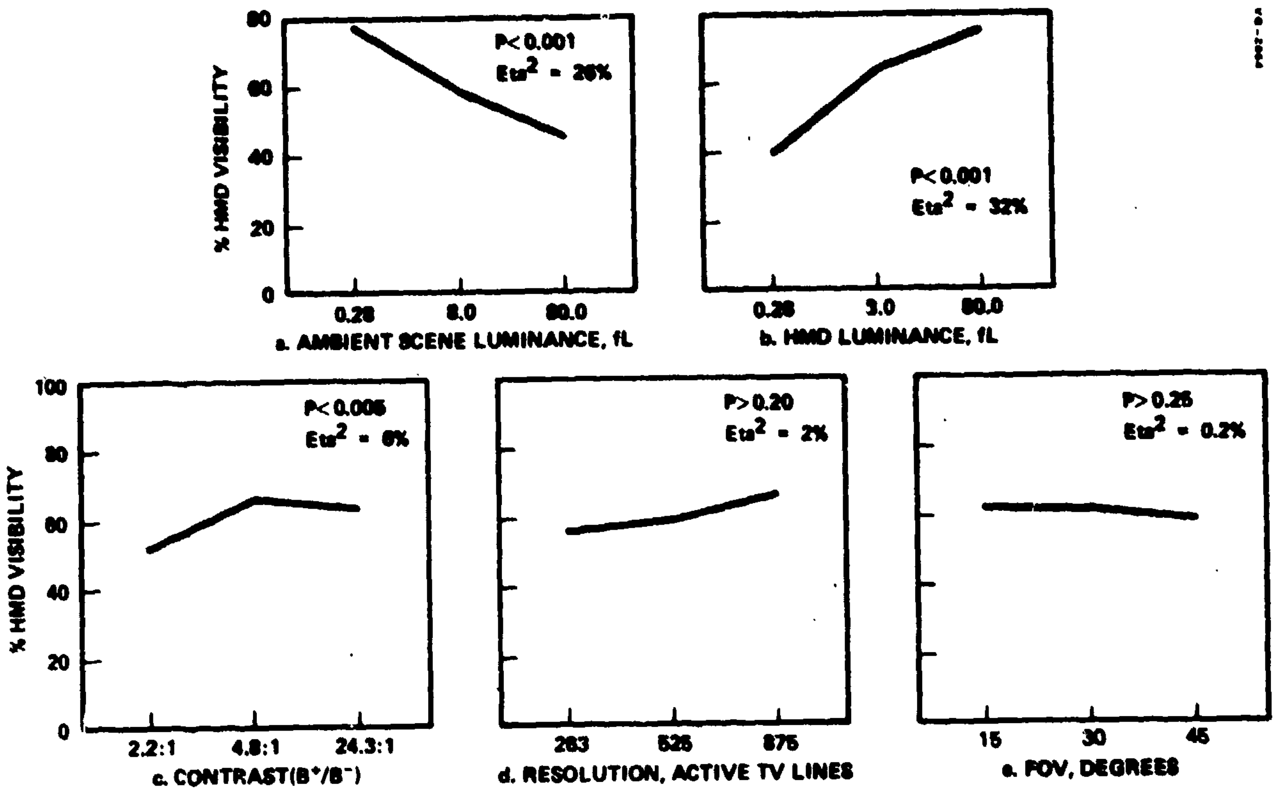


Figure 21. Results of the parametric study.

The largest effects were due to the two luminance conditions. As expected, HMD visibility scores were positively correlated with HMD luminace and inversely related to ambient scene luminance. The large effects of the luminance conditions can be attributed to the larger range over which these parameters were varied compared with the range of values of the same parameters in the screening study.

The effect of contrast was also larger in the parametric study than in screening study (6 percent versus 1.4 percent of the total variance, respectively) which, again, can be attributed to the greater range of values investigated. It can be seen in Figure 21.c that HMD visibility increases from the low to medium contrast values, but remains virtually unchanged from medium to high contrast. It appears that contrast effects are most salient at the lower values. Beyond a certain point, increased contrast apparently has little influence on contour strength.

Resolution failed to significantly effect HMD visibility scores in the parametric study, while the effect of this parameter was large in the screening study, accounting for 9 percent of the total study variance. It can be seen from Figure 21d that the highest and lowest resolution values differ by only 7.2 percentage points. It should be noted, however, that the lowest resolution value used in the parametric study was 263 TV lines while the lowest screening study value for this parameter was 165 TV lines. The effect of resolution may also be minimal beyond some threshold value lying between 165 and 263 TV lines.

The effect of HMD field of view also had no significant effect on visibility scores. Figure 21e shows the slope of the curve for this parameter to be nearly level. The effect of FOV for the parametric study is not consonant with the results of the screening study, where this parameter showed significantly higher HMD visibility scores for the 15-degree FOV condition. Because of the discordant results of the parametric and screening studies, the effect of HMD field of view on the measure of binocular rivalry used in these studies is uncertain. In any case, the effect, if any, is not large and is likely a trivial one. The significant effect of FOV in the screening study accounted for only 2.1 percent of the total variance.

Conclusions

It appears that while image related parameters such as resolution and contrast affect binocular rivalry, their influence is only manifest at low operational levels which are impractical or undesirable in operational situations. Reducing binocular rivalry by severely degrading HMD image quality, to make the ambient scene predominant, is not a practical solution to the problem. Low resolution and low contrast HMDs are not recommended. The information gleaned from the present studies with regard to the effect of resolution and contrast on binocular rivalry in HMD systems is not without merit, however. The binocular rivalry problem with such systems is manifest when the operator wishes to attend to either the HMD or ambient scene and experiences competition from the contralateral field. For example, instrument reading may be impeded by binocular conflict from the HMD image. In such cases, binocular rivalry may be reduced, relative to the ambient scene, if the pilot is provided the capability of reducing HMD image related parameter values via controls provided for that purpose. For example, the pilot could simply turn the HMD brightness or contrast down to eliminate any binocular rivalry and make the ambient scene predominant.

HMD and ambient scene luminance produced the largest effects on HMD visibility scores, together accounting for 58 percent of the total variance. Figures 21a and 21b show the functional relationship of the two luminance parameters to HMD visibility scores. HMD luminance is positively related to HMD visibility, while ambient scene luminance bears an inverse relationship to HMD visibility. Scene luminance, therefore, appears to be the key parameter for the incidence and control of binocular rivalry and the resultant scene visibility.

VALIDATION STUDY

Purpose

The screening and parametric studies provided data to establish HMD conditions to which binocular rivalry is sensitive, using a quantitative, continuous judgmental performance criterion measure. The validation study was conducted to determine if these conditions differentially affect operator performance on real-world tasks and thereby validate the judgmental performance measure used in the screening and parametric studies.

Any situation where a disparate image is presented to each eye produces binocular rivalry. Image related parameters may be manipulated to enhance one image while suppressing the other in a binocular rivalry situation, but this is not to say rivalry has been reduced or eliminated. Binocular rivalry is still present, albeit only one image is perceived, since the other is totally or almost totally suppressed by the dominant field. Binocular rivalry is eliminated entirely only when one of the disparate images is removed. With HMD systems, for example, rivalry is eliminated if the operator closes the non-HMD eye so that the HMD image is seen without interference, or conversely, if the HMD is shut off so that only the ambient scene is seen. Binocular rivalry is not present (by definition) in either of the above situations, but both are operationally untenable. It is thus not possible to talk about reducing (or eliminating) binocular rivalry independently of which visual field dominates or suppresses the other. Rivalry can only be considered reduced with specific reference to one of the visual fields. Reducing rivalry in terms of increasing the saliency of the image of a particular visual field, increases rivalry with respect to the reduced saliency of the contralateral visual field.

In the validation study, the effects of binocular rivalry on operator performance were examined at three levels specific to each visual field using separate tasks. For the HMD visual field, a target recognition task was used to determine the effects of 1) no binocular rivalry, 2) a rivalry situation where the HMD visual field was enhanced, and 3) a rivalry situation where the HMD visual field was suppressed. A tracking task was employed to determine the effects of the three binocular rivalry conditions when the operator was required to attend to the ambient visual field.

To simulate the above conditions, two HMD and two ambient scene configurations were employed. Since luminance was the only ambient scene parameter (other than scene complexity) found to significantly effect HMD visibility, only this parameter was varied for the ambient scene. For the HMD scene, two levels of resolution, contrast, and luminance combinations were examined. The two configurations of each visual field were qualitatively designated as the good and poor conditions. The good and poor configuration of each visual image was examined at both configurations of the contralateral visual field. In addition, to provide baseline data, both configurations of each field were examined where no contralateral image was present, i.e., where binocular rivalry was absent. This resulted in a comparison of six conditions for each task.

A seventh condition, a bifocular HMD configuration which used the good configuration for both the HMD and ambient fields, was also examined. The bifocular condition is a method of eliminating binocular rivalry by placing the center of the HMD below the horizontal line of sight. Thus, when the operator is attending to the ambient scene, the HMD is not in the line of sight of either eye and binocular conflict is prevented. To view the HMD, the operator shifts his eyes downward, as when using bifocal eyeglasses. Since the ambient scene perceived by the non-HMD eye which results from this angle of view is of a darkened cockpit area, binocular conflict with the HMD image is greatly reduced.

For each task, seven conditions were examined, five of which were identical for each task. The two conditions for each visual field which had no competing field (no rivalry) were task specific. In all, nine experimental conditions were examined. These are shown in Table 12.

TABLE 12. EXPERIMENTAL CONDITIONS FOR VALIDATION STUDY

Condition	HMD Configuration	Ambient Scene Configuration	Task
1.	Good	None	Target recognition only
2.	Good	Low	Target recognition and tracking
3.	Good	High	Target recognition and tracking
4.	Poor	None	Target recognition only
5.	Poor	Low	Target recognition and tracking
6.	Poor	High	Target recognition and tracking
7.	None	Low	Tracking only
8.	None	High	Tracking only
9.	Good (Bifocular)	High	Target recognition and tracking

Apparatus

The equipment described in the Laboratory Equipment Section was modified for the validation study in the following way. The ambient scene was not optically projected as it was in the screening and parametric studies; consequently, the projection screen for this scene was removed. In its place, a 3 by 3-foot plywood board, painted flat black, was mounted to the apparatus table directly in front of the operator and perpendicular to his line of sight. An enlarged (full scale) color print of the F-14 front cockpit used in the screening study was mounted on the board. A 2-1/2 inch diameter galvonometer was then inserted into the plywood directly covering one of the dials on the color print. To reduce glare from ambient lighting, the glass was removed from the instrument. This dial was to serve for the tracking task. Figure 22 shows the modified apparatus.

Figure 22. Research apparatus for validation study.

The control lever for measuring HMD visibility was removed and a laterally tracking joystick was mounted in its place. This was the control for the ambient scene tracking task.

The galvonometer indicator moved across the dial face in response to a pure sine wave input from the Miniac computer. By moving the control lever laterally in response to a sine wave of opposite phase, the dial indicator could be kept at the null (center) position. The computer measured the error between the sine wave input and the control lever output to provide tracking error scores.

The projector used to project the ambient scene in the screening and parametric studies was removed from its tripod and placed on a small stand to the right of the seated operator on the apparatus table. This projector was used, without slides, to provide controlled lighting for the ambient scene. Ambient scene luminance was adjusted by varying the size of the projector iris diaphragm aperture.

A digital readout timer was used to measure target recognition time. Subjects were provided a response button which stopped the timer upon target recognition.

Imagery

The ambient scene was not optically projected and thus required no imagery. Because of the target recognition task requirement that any target image be seen only once to preclude subjects learning the targets' location, seven targets were selected for presentation, one for each target recognition task condition. The targets were two command posts (two targets), a truck within a truck park, a self-propelled gun emplacement, a tank in a column, a SAM missile, and two automobiles (one target). Two example targets are shown in Figure 23. The targets are circled for identification in Figure 23. They were not circled when presented to the subjects.

The 4- by 4-inch positive transparency target imagery was placed in the Hughes Remote Piloted Vehicle (RPV) Simulator and photographed off the RPV display on 35-mm positive transparency film. Resolution and contrast values were adjusted with controls incorporated into the RPV simulator for that purpose.

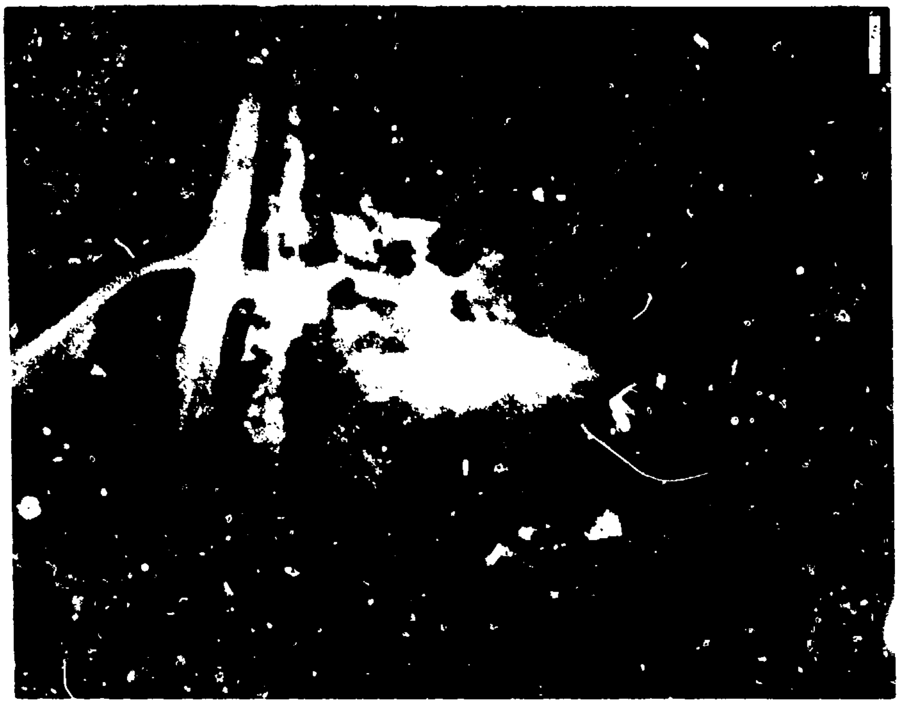
Operational Definitions of Experimental Conditions

The good HMD condition was defined as 650 active TV line resolution, 29:1 contrast (B_{max}/B_{min}), and 10 fL luminance. The luminance value was the average scene luminance limited by projector output and the transmittance of the most dense target transparency.

The poor HMD condition was defined as 240 active TV lines, 6:1 contrast (B_{max}/B_{min}), and 0.3 fL luminance. These latter levels were considered minimal operational values. Figures 24 and 25 show two target images for the good and poor HMD conditions.

The quality of the ambient scene could be altered only through luminance changes. This was accomplished by using the slide projector as a light source to illuminate the cockpit color print and the tracking dial.

Figure 23. Two example targets used in validation study.



a. Good HMD

b. Poor HMD

Figure 24. Example target used in validation study at good and poor HMD configurations.

a. Good HMD

b. Poor HMD

Figure 25. Example target used in validation study at good and po. r HMD configurations.

The high ambient scene condition was defined as having 10 fL reflected luminance. Luminance readings were taken from the dial area of the color print.

The low ambient scene condition was defined as having 0.3 fL reflected luminance. For the HMD and ambient scene no-rivalry conditions, the respective projectors were turned off.

HMD field of view was 30 degrees. Since the operators' task with respect to the ambient scene required monitoring a cockpit dial, this scene was placed 30 inches from the subjects' eye. The HMD was accommodated at infinity and presented to the left eye. HMD transparency was 0.05 percent and the display was unframed.

Dependent Measures

The dependent measure for the target recognition task was target recognition time measured in 10ths of a second. The dependent measure for the tracking task was integrated tracking error measured in volts.

Operator Tasks

For the target recognition task, the operator was required to search the HMD scene for the prebriefed target, press the response button upon locating the target, and point the target out on the screen so that the experimenter could determine if the correct target has been recognized. The tracking task required the operator to keep the ambient scene dial indicator at the null position for a 60-second trial.

Subjects

Five Hughes engineers and two Air Force personnel served as subjects.

Research Design

The target recognition and tracking tasks were analyzed as separate experiments. Since unique experimental design applications were required for each dependent measure, a different experimental design was employed in each case.

A 7 by 7 Latin square was used to balance the seven conditions within the seven targets and seven subjects for the target recognition task. Figure 26 shows the Latin square arrangement. The seven conditions within the square correspond to the condition numbers listed in Table 12. Order of presentation was randomized for each subject within the restriction of balance required for the Latin square. With this design, the main effects of subjects and targets were removed, thus increasing the precision of estimates of study conditions effects.

TARGETS

SUBJECTS	1	2	3	4	5	6	7
1	1	2	3	4	5	6	9
2	2	3	4	5	6	9	1
3	3	4	5	6	9	1	2
4	4	5	6	9	1	2	3
5	5	6	9	1	2	3	4
6	6	9	1	2	3	4	5
7	9	1	2	3	4	5	6

C7622/2990

Figure 26. Experimental design for the target recognition task.

A balanced randomized blocks design was used for the tracking task. This design is shown in Figure 27.

TREATMENTS

SUBJECTS	2	3	5	6	7	8	9
1							
2							
3							
4							
5							
6							
7							

C7622/2991

Figure 27. Experimental design for tracking task.

The seven treatment conditions correspond to the conditions numbered in Table 12. Order of presentation was randomized and subjects were randomly assigned to blocks. The effects due to differences among subjects were removed from estimates of conditions effects with this design.

Both of the above designs were replicated once, since even two replications would require double the experimental effort. The single replication precluded an estimate of within cell error. If the assumption that all two and three-factor interactions are negligible could be validly made, the pooling of these interactions could be considered an estimate of experimental error. This assumption, however, was not considered valid, particularly with respect to the target by treatment interaction in the target recognition task. Hence it was expected that the error terms would be large and the power of significance tests of treatment effects reduced. For this reason, alpha level was set at 0.20 rather than the conventional 0.05 to increase the power of the statistical tests, since it was considered more costly to overlook a true difference between conditions than to falsely accept the null hypothesis of no difference.

Procedure

Subjects were brought into the laboratory, seated at the apparatus, and given a copy of the experiment instructions (see Appendix B). After reading the instructions, the apparatus was adjusted and aligned for each subject to ensure that the HMD scene was properly framed in the beam splitter and superimposed on the ambient scene in the correct position. The superimposition placed the ambient scene tracking dial in the center of the HMD scene. Once the equipment adjustments were made, the following procedure was followed on all training and test trials.

Subjects were shown sketches of the target scene prior to each trial. After being briefed on the target, the subject placed his head in the chin rest, closed his eyes, and signalled the experimenter when he was ready to begin. The experimenter then inserted the correct target slide in the projector and said, "One, two, three, start," and started the digital timer. On the command "start", the subject opened his eyes and immediately searched the HMD scene for the target. When the subject located the target, he pressed his response button to stop the timer and then pointed to the target he had recognized so the experimenter could determine whether or not he was correct. Recognition time scores were recorded on prepared data sheets.

Following each target recognition trial (except for the two conditions where the ambient scene projector was turned off), tracking task trials were conducted. For this task, the subject again started with his eyes closed and on the experimenter's command "start", opened his eyes and attempted to keep the dial indicator at the null position using the control. The computer sine wave input was initiated simultaneously with the command "start" and was programmed to stop automatically after 60 seconds. Tracking error scores were read off the computer display and entered on the data sheets. Each subject was given the nine test conditions.

For the no-rivalry target recognition conditions, the ambient scene projector was turned off. Since all trials were conducted with no ambient room illumination, no interference from the ambient scene was present, since it was not visible. Conversely, the HMD projector was turned off for the tracking task no-rivalry conditions.

Subjects were given three training trials on each task prior to data collection to familiarize them with the apparatus and experimental procedures.

Results and Discussion

For the two cases where target recognition was incorrect, recognition time scores of 20 seconds were used for analysis. The longest time for a correct recognition was 18 seconds. Table 13 shows the analysis of variance summary table for target recognition time scores.

TABLE 13. ANALYSIS OF VARIANCE SUMMARY: TARGET RECOGNITION TIME

Source	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Significance Level	Percent Eta^2
Between Subjects	124.68	6	20.78			12
Within Subjects	544.62	42				
Conditions	319.14	6	53.19	4.58	<0.005	32
Targets	225.48	6	37.58	3.24	<0.025	22
Residual	348.37	30	11.61			34
Total	1017.67	48				

As expected the error term was large, accounting for 34 percent of the total variance. In spite of this, the HMD conditions effects were highly significant and accounted for 32 percent of the variance.

Given the significant overall F test for treatment effects, the Scheffe method of post-hoc comparisons was used to evaluate comparisons among means. Unlike planned comparisons, there is no requirement that post-hoc comparisons be independent. The significance of comparisons using the Scheffe method are found by the use of confidence intervals. Any confidence interval that excludes zero is considered significant and identified as one possible contributor to the overall significance. The meaning of the confidence intervals for the Scheffe post-hoc comparisons is interpreted as follows. Considering all possible comparisons, the probability is one minus alpha that each confidence interval is true simultaneously for all comparisons.

That is, for alpha set at 0.20, there is a 20 percent chance that one or more confidence intervals will not cover the corresponding true comparison value.

Figure 28 and Table 14 show the mean target recognition time scores in seconds for the seven conditions.

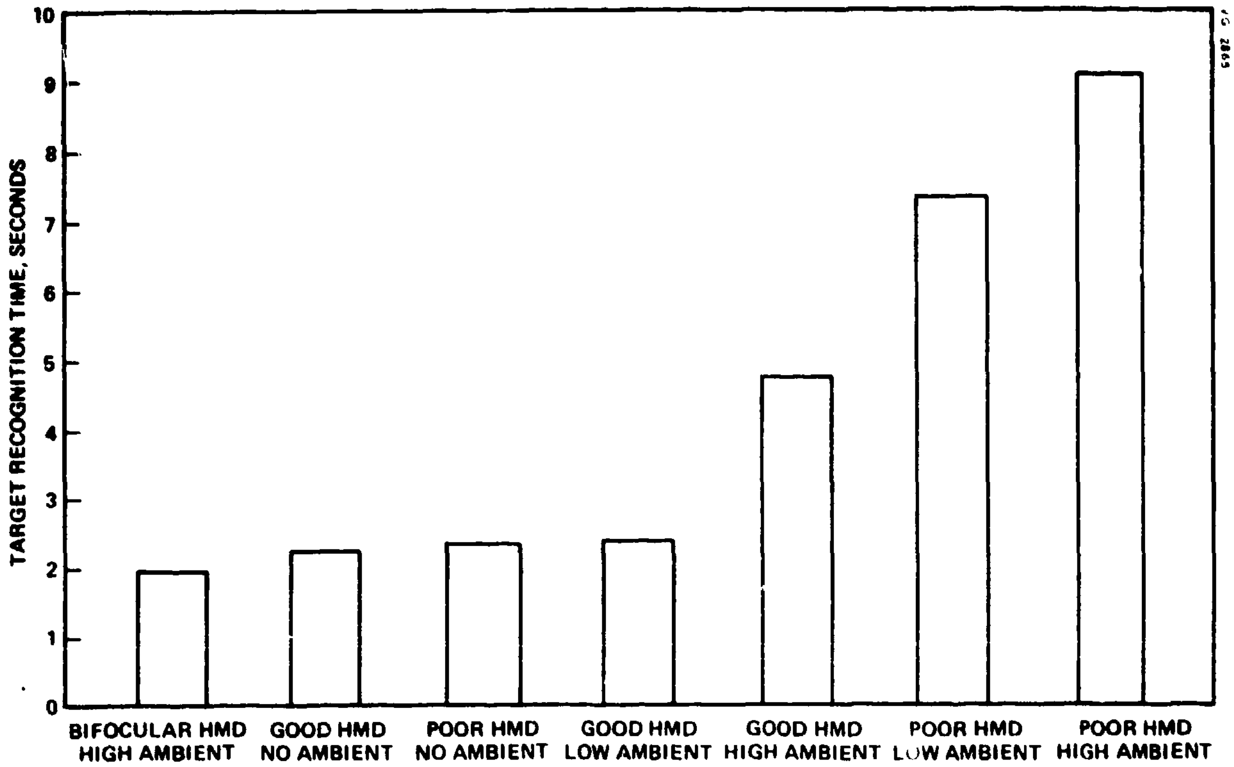


Figure 28. Validation study target recognition time performance for all conditions.

TABLE 14. MEAN TARGET RECOGNITION TIME, SECONDS

Condition	HMD Configuration	Ambient Scene Configuration	Mean Time, Seconds
1	Good	None	2.26
2	Good	Poor	2.36
3	Good	Good	4.74
4	Poor	None	2.34
5	Poor	Poor	7.43
6	Poor	Good	9.06
9	Good (Bifocular)	Good	1.96

Table 15 shows the confidence intervals for the comparisons of interest with alpha equal to 0.20.

TABLE 15. CONFIDENCE INTERVALS FOR COMPARISON OF TARGET RECOGNITION TASK CONDITION MEANS

Comparison	Conditions	Confidence Interval	Significant Effects
1. Good vs poor HMD, no ambient	1 vs 4	$-5.61 \le \phi_1 \le +5.45$	
2. Good vs poor HMD, low ambient	2 vs 5	$-0.40 < \phi_2 \le +10.60$	
3. Good vs poor HMD, high ambient	3 vs 6	$-9.85 \le \phi_3 \le +1.11$	
4. Good vs poor HMD, all ambients	$\overline{1, 2, 3}$ vs $\overline{4, 5, 6}$	$-6.10 \le \phi_4 \le -0.22$	*
5. High vs low ambient, poor HMD	5 vs 6	$-7.16 < \phi_5 \le +3.90$	
6. High vs low ambient, good HMD	2 vs 3	$-3.15 \le \phi_6 < +7.91$	
7. High vs low ambient, all HMDs	$\overline{3, 6}$ vs $\overline{2, 5}$	$-4.22 \le \phi_7 \le +0.22$	
8. Good HMD, low ambient vs poor HMD, high ambient	2 vs 6	$-12.23 - \phi_8 \le -1.17$	*
9. Good HMD, high ambient vs poor HMD, low ambient	3 vs 5	$-2.84 \le \phi_9 \le +8.22$	
10. Rivalry vs no rivalry	$\overline{2, 3, 5, 6}$ vs $\overline{1, 4, 9}$	$+0.66 \le \phi_{10} \le +6.74$	*
11. Bifocular vs rivalry	9 vs $\overline{2, 3, 5, 6}$	$+0.29 \le \phi_{11} \le +7.59$	*

The comparisons of the good versus poor HMD configurations at each ambient condition (comparisons 1, 2 and 3) were not significant, while the same comparison (4) averaged across all three ambient conditions was significant. The reason for this is that the averaged comparison represents a larger number of data points; hence the estimate is more precise. This can be seen in the smaller confidence interval for comparison 4 as compared with comparisons 1, 2 and 3. In such cases, the average should be considered the best estimate of the true treatment effect. Therefore, the null hypothesis of no difference between the good and poor HMD configurations was rejected. It can be seen from Figure 29, which shows the comparison of the treatment means for comparison 4, that the good HMD configuration produced faster target recognition times than the poor HMD configuration by a factor of two.

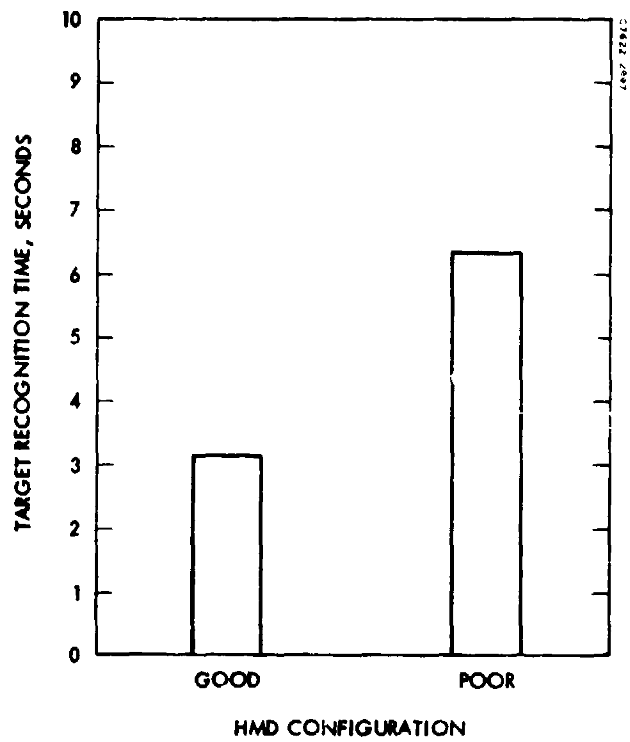


Figure 29. Mean target recognition time for good versus poor HMD configurations.

Individual comparisons of good versus poor ambient luminance conditions for both the good and poor HMD configurations (comparisons 5 and 6) were not significant, nor was the high versus low ambient luminance condition comparison (7) when averaged across both HMD configurations. It was thus concluded that the two ambient luminance conditions had no major effect on the HMD target recognition task. Figure 30 shows the comparison of ambient luminance condition means, averaged across HMD conditions.

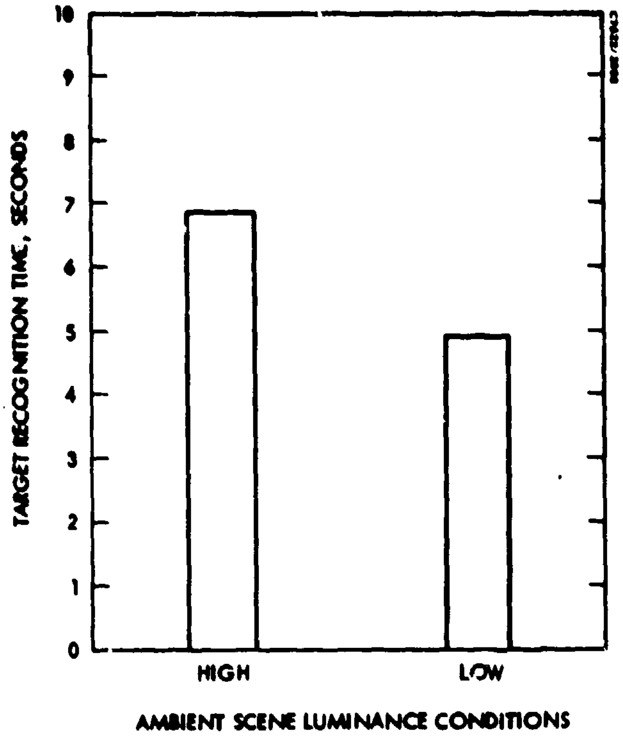


Figure 30. Mean target recognition time for high versus low ambient scene luminance conditions.

The rivalry situations which favored neither the HMD nor the ambient scene, i. e., the good HMD/high ambient and poor HMD/low ambient conditions, showed no significant differences in target recognition scores (comparison 9). However, the rivalry condition which favored the HMD scene, i. e., good HMD/low ambient, produced significantly faster target recognition times than the rivalry condition which favored the ambient scene, i. e., poor HMD/high ambient (comparison 8). These comparisons are shown in Figures 31 and 32, respectively. While Figure 31 shows lower recognition times for the good HMD/high ambient condition than for the poor HMD/low ambient condition, the difference was not significant.

A comparison of the mean scores of the rivalry versus no-rivalry conditions (comparison 10) was significant. This comparison is depicted in Figure 33. The mean score of those conditions where rivalry was absent was significantly lower than the average of the conditions in which binocular rivalry was present.

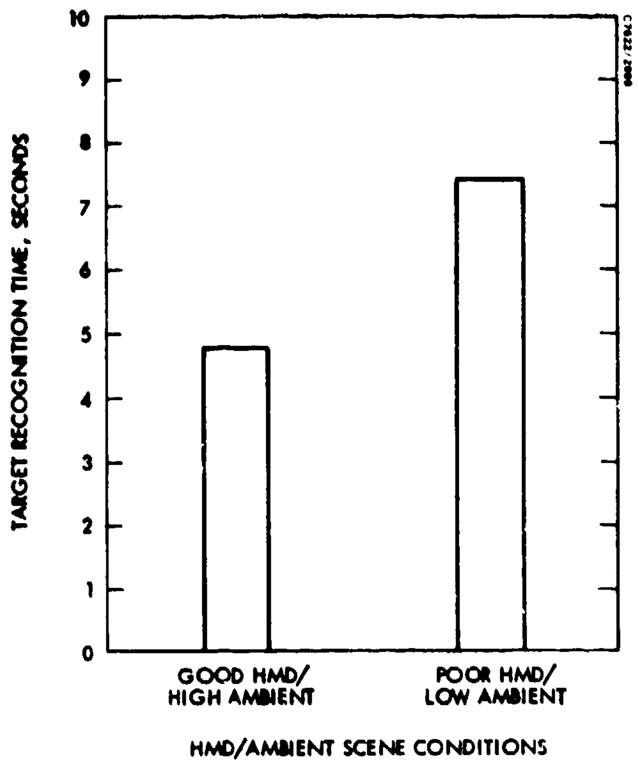


Figure 31. Mean target recognition time for good HMD/high ambient versus poor HMD/low ambient conditions.

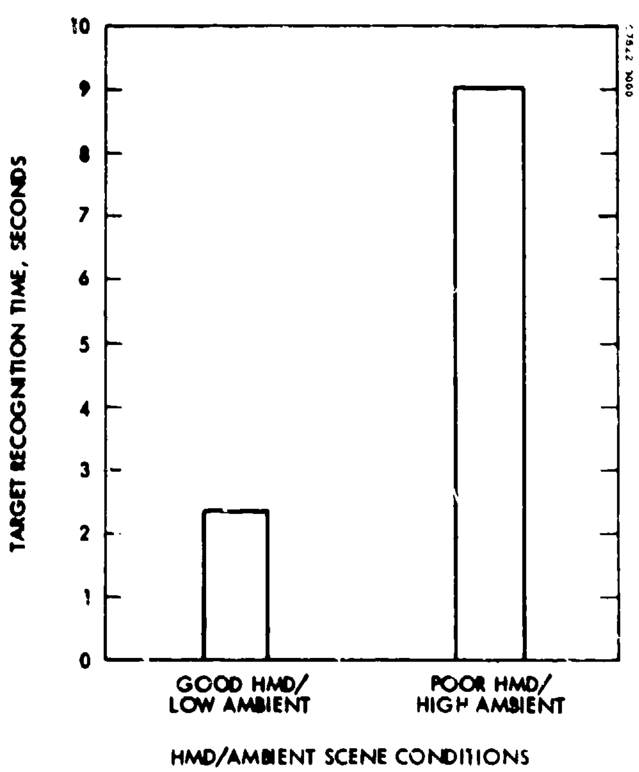


Figure 32. Mean target recognition time for good HMD/low ambient versus poor HMD/high ambient conditions.

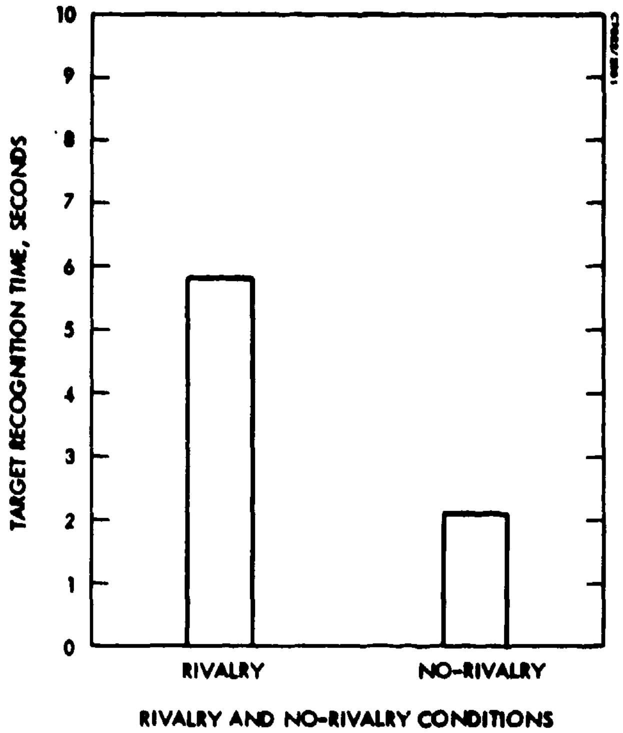


Figure 33. Mean target recognition time for rivalry versus no-rivalry conditions

The bifocular HMD configuration was a no-rivalry condition wherein both scenes were extant. This condition was compared with the average of those conditions where rivalry was present (comparison 11) and the difference in recognition time scores was found to be significant. Figure 34 shows the bifocular HMD configuration times to be significantly faster than the times averaged across the rivalry conditions.

Tracking task scores were calculated as a proportion of maximum tracking error. Table 16 shows the analysis of variance summary table for tracking error scores.

There were no significant differences in tracking error scores, either among subjects or among HMD conditions. The F-ratios for both between and within subjects effects are very close to unity, the theoretical value of F when no true differences exist. It must be concluded, then, that HMD/ambient conditions had no effect on tracking task performance. This outcome was not expected but pilot studies with the apparatus and observational data during the study indicated that the various HMD configurations did not influence tracking task performance in any way. Because of this, subjects were asked upon completion of the test trials if the HMD interfered at any time with the tracking task. All seven subjects responded negatively. The

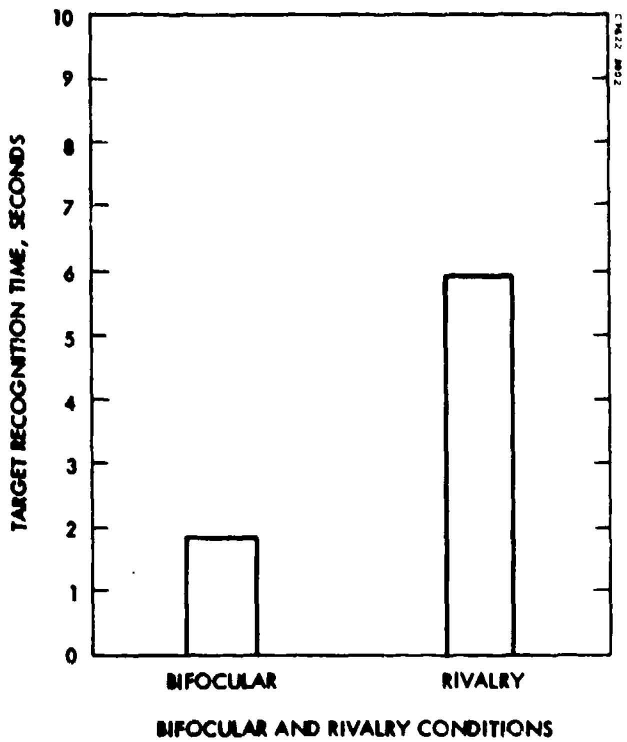


Figure 34. Mean target recognition times for the bifocular HMD configuration versus the average of the rivalry conditions.

TABLE 16. ANALYSIS OF VARIANCE: TRACKING ERROR

Source	Sums of Squares	Degrees of Freedom	Mean Squares	F-Ratio	Significance Level	Percent Eta^2
Between subjects	434.64	6	72.44	1.38	> 0.25	18.2
Within subjects	1946.52	42	46.34	0.88	>0.25	
Conditions	50.67	6	8.44	0.16	>0.25	2.2
Residual	1895.85	36	52.66			79.6
Total	2381.16	48				

ambient scene visual field interfered with operator performance with respect to the HMD scene, but the reverse was not true. There are at least two possible explanations which may resolve this enigma.

First, the movement of the dial indicator may be an attention getting factor which influenced the predominance of the ambient scene. It was observed in the qualitative laboratory evaluation that a dynamic HMD target did not decrease the incidence of rivalry compared to a static scene. In a discussion of binocular rivalry, Dember (1960) states that "movement, whether of the eye or of the target, is thus, a powerful inhibitor of rivalry." The effect of movement in the disparate images in binocular rivalry is not clear. During the validation study, it was observed, however, that although the ambient scene tended to fade out during rivalry, including parts of the tracking dial, the indicator and adjacent index markings were always visible, and this portion of the image was sufficient to perform the tracking task as if no rivalry were present. It is not known whether the resistance of the dial indicator and adjacent index markings to fade out can be attributed to the movement of the dial indicator. Further research is needed to answer this question.

A second possible explanation for the failure of the HMD conditions to affect tracking task performance may be the relative difference in resolution between the two visual fields. The HMD scene averaged 425 active TV lines while the resolution of the ambient scene was limited by the acuity of eye. This difference in resolution between the two visual fields may have accounted for higher ambient scene predominance.

Most likely both dial indicator movement and the higher resolution of the ambient scene contributed to the greater predominance of the ambient field. However, since it was observed that portions of the tracking task dial did fade out and reappear in typical alternating fashion during rivalry, it is felt that dial indicator movement was largely responsible for the invariant tracking performance scores across all HMD conditions.

Conclusions

In summary, the following results obtained in the validation study:

1. The good HMD configuration produced significantly better target recognition performance than the poor HMD configuration.

2. Target recognition performance was significantly degraded when binocular rivalry was present compared with no-rivalry conditions.

3. With binocular rivalry, target recognition performance was significantly better when conditions favored the HMD than when conditions favored the ambient scene.

4. Target recognition performance was significantly better for the bifocular HMD configuration compared with HMD configurations in which rivalry was present.

5. Tracking performance was unaffected by binocular rivalry.

The validation study confirms the hypothesis that the amount of binocular rivalry induced through manipulation of HMD parameters related to the phenomenon is related to operator performance on realistic HMD and non-HMD tasks.

Levelt (1965) suggests that the predominance of a visual field in binocular rivalry is a function not of the stimulus strength of the same stimulus, but only of the contralateral stimulus. In the present study, it has been argued that the stimulus strength of the ambient scene was greater than that of the HMD scene, since resolution of the former was limited only to the visual acuity of the eye. Manipulation of the stimulus strength of the ambient scene through reduced luminance, or complete absence of the scene, would be expected to increase the predominance of the HMD scene and consequently result in improved target recognition performance. This was indeed the case. On the other hand, the level of performance on the tracking task with reduced HMD stimulus strength, or complete absence of the HMD image, was not affected by increasing the HMD stimulus strength, perhaps because of the inherently superior stimulus strength of the ambient scene. It should be noted, however, that HMD stimulus strength could, and normally would be, increased by higher luminance values than the imagery and equipment limited 10 fL used in the present study. It is likely that greater luminance disparity between the visual fields, with high HMD values, would reduce ambient scene predominance and consequently degrade tracking performance. Further research should be directed toward answering this question. However, the HMD luminance limitations of the present study notwithstanding, it appears that the binocular rivalry problem in HMD systems is more critical with regard to information retrieval from the HMD than from the ambient scene. Furthermore, the binocular rivalry problem is apparently obviated with the bifocular HMD configuration. Target recognition time scores were lower for this condition than for any other and were significantly lower than the average of the conditions in which rivalry was present.

The design implications of the four laboratory research studies are discussed in the following section.

SECTION 4.

IMPLICATIONS OF THE LABORATORY RESEARCH FOR DESIGN AND USE OF HELMET-MOUNTED DISPLAYS

Binocular rivalry has been defined as a perceptual fluctuation resulting from disparate images formed on the retina of each eye so that binocular fusion of the two images cannot occur. The perceptual conflict in binocular rivalry results in the perception of some mosaic consisting of parts of both fields. This pattern is unstable and the conflict is apparently resolved by the visual system through perceptual alternation of the two images. The rate of alternation and predominance of either image appears to be a function of the stimulus strength of the stimuli. Levelt (1965) has suggested that the duration of a dominance period for a given eye is not dependent on the strength of the stimulus presented to that eye, but only on the strength of the image presented to the contralateral eye. Levelt (1965) assumed that the stimulus strength of a pattern in binocular alternation is directly related to the strength of its contours. Contour strength is a function of such HMD parameters as resolution, contrast, and luminance.

The present research has shown that the above parameters do indeed affect image predominance in binocular rivalry. The relevant question is how binocular rivalry can be eliminated or reduced in HMD systems through manipulation of image-related parameters. Such a question cannot be answered, however, independently of which visual field will be selected to dominate the other. This qualification is important, since operational use of HMDs requires information retrieval from both visual fields.

The present research has shown that reduction of HMD resolution, contrast, and luminance results in reduced binocular conflict, as manifested by increased predominance of the ambient scene, and produces concommitant degradation of HMD target recognition performance. The latter consequence of reducing binocular rivalry by reducing the contour strength of the HMD image precludes this method as a practical solution to the problem. Furthermore, the validation study showed that attenuation of binocular rivalry through manipulation of HMD related parameters had no effect on an ambient scene tracking task. It is not recommended that HMD resolution and contrast be reduced as a means of reducing binocular rivalry. HMD resolution and contrast need rather to be specified as a function of operator performance requirements on HMD related tasks.

Within the limits of the parameter values used in the validation study, it was demonstrated that an HMD of good resolution, contrast, and luminance produced the same level target recognition performance regardless of ambient scene conditions. The difference in mean recognition time between the no-rivalry (no ambient scene) condition and the low-rivalry (low ambient luminance) condition was a mere 1/10 of a second. On the other hand, the high-rivalry (high ambient luminance) condition mean recognition time was more than double the low-rivalry condition. The implications of the parameters investigated in the laboratory research to HMD design are discussed below.

HMD RESOLUTION

The screening study showed HMD resolution to have a statistically significant effect on HMD scene visibility. The parametric study, however, did not show resolution to have a statistically significant effect on HMD scene visibility. The major difference between the two studies which probably accounts for this was the lower resolution (165 lines) value used in the screening study. The lower value used in the parametric study was 263 lines. The trend for HMD image visibility to improve with increased resolution was obtained in the parametric study, but the effect was small. Apparently HMD resolution has only a minor effect, except at very low resolutions where contour sharpness becomes very poor. For state-of-the-art display system resolution levels, resolution is not a parameter which has an important effect on binocular rivalry with HMDs.

HMD FIELD OF VIEW

The field of view (visual subtense of the HMD) had a statistically significant but relatively small performance effect on HMD image visibility. The smaller 15-degree field of view produced a 7 percent higher HMD visibility score than did the larger 45-degree field of view. In the parametric study, 15-, 30-, and 45-degree fields of view were investigated, and only a 2 percent performance variation, non-significant effect was found. It had been hypothesized that smaller fields of view would provide perceptually sharper contours and hence greater HMD visibility than larger fields of view. This was not found to be the case within the practical range of the 15- to 45-degree HMD fields of view investigated in the parametric study. Therefore, HMD field of view does not appear to be a parameter that is important in HMD design with respect to binocular rivalry.

LUMINANCE OF HMD AND NON-HMD SCENES

HMD and ambient scene luminance both had statistically significant effects on HMD visibility, together accounting for 10 percent of the variance in the screening study. In the parametric study, a broader range of luminance was investigated and highly significant effects were obtained. HMD and ambient luminance together accounted for 58 percent of the variance in the parametric study.

Of all the HMD design parameters investigated, luminance had the largest effect on binocular rivalry. Large HMD luminance relative to ambient scene luminance results in dominance of the HMD scene. Large ambient scene luminance relative to HMD luminance results in dominance of the ambient scene. A major potential for dealing with binocular rivalry in HMDs resides in the control of the luminance of the HMD and ambient scenes. Additional research should, therefore, be concentrated on those parameters that effect luminance, namely HMD luminance, visor transmittance, HMD combiner transmittance, displayed information (symbology and sensor video), and ambient illumination (day and night missions) to achieve an HMD design which minimizes the effects of binocular rivalry and satisfies mission and operator task performance requirements.

COMBINER TRANSMITTANCE

Occluded (zero transmittance) and 10 percent transmittances were investigated in the screening study. The effect of combiner transmittance was not found to be statistically significant ($p > 0.25$) and accounted for only 0.2 percent of the variance in the screening study. This was somewhat of a surprise in view of the observations made by Jacobs, Triggs, and Aldrich (1970) and the significant effect of ambient scene luminance.

Combiner transmittance determines the amount of ambient scene luminance that reaches the HMD eye. It had been hypothesized that if the ambient scene was visible to both eyes, even though of different intensity, there would be less binocular rivalry. Apparently, it is the relative intensity of the disparate scenes presented to the two eyes that has the major effect on the occurrence of binocular rivalry. This does not mean that combiner transparency is not an important parameter in HMD design. With large transmittances in high ambient luminances, HMD image quality is severely affected. In the following section of this report, an analysis of HMD image quality which treats HMD luminance, HMD combiner transmittance, and ambient illumination is presented.

HMD CONTRAST

The effect of target contrast in the HMD scene was investigated in the screening study and found to have a significant effect on HMD visibility. In the parametric study, the range of contrast investigated (2.2:1 to 24.3:1) was extended and contrast was again found to have a significant effect, accounting for 6 percent of the variance. The effect, however, was only present between the two lower contrast values — 2.2:1 and 4.8:1. Apparently, the effect of contrast on binocular rivalry is important only at low values of contrast. When moderate contrasts are obtained, further increases in contrast do not result in additional increases in HMD scene visibility. For HMD design, conditions that result in low scene contrast should be avoided, e.g., combiner transparencies and ambient scene luminances that result in washed-out HMD scenes. The HMD operator can control HMD scene contrast with the HMD contrast and brightness controls and thereby avoid low contrast scenes. If a see-through HMD is used, adjustable combiner transmittance could be used to obviate loss of contrast due to ambient scene luminance.

HMD AND AMBIENT SCENE ACCOMMODATION

Accommodation distances of 30 inches and infinity were investigated for both HMD and ambient scenes in the screening study. It was hypothesized that if the HMD and ambient scenes were presented at different accommodation distances the operator could focus to the scene he wanted to see to the exclusion of the second scene and thereby overcome binocular rivalry. An interaction between HMD accommodation and ambient accommodation was therefore predicted. The results did not reveal this interaction. Hence, different accommodation distances for the HMD and the ambient scene is not a solution to reducing or eliminating binocular rivalry.

HMD accommodation had a statistically significant effect on HMD scene visibility, accounting for 4 percent of the variance. When the HMD scene was collimated to infinity, superior HMD scene visibility was obtained -- 76 percent compared to 65 percent for the 30-inch accommodation distance. Since HMD accommodation distance is unrelated to the image contour strength or any other theoretical explanation of binocular rivalry, the cause of this finding is presently unexplainable. HMDs are in general designed to be collimated to infinity; hence, this finding is not counter to present design philosophy. Such a finding is, nevertheless, unresolved at this time.

HMD COLOR

A monochrome versus a color HMD was tested in the screening study and found to have no effect on binocular rivalry. Mean percent HMD visibility was the same for monochrome and color HMDs. The use of a monochrome or color HMD, therefore, will have no effect on the incidence of binocular rivalry with HMDs.

HMD FRAMING

A visor projected type HMD was compared to a side-mounted type HMD in the screening study. With the visor-projected HMD, the HMD image is seen as a superimposed part of the overall external visual field of view by the HMD eye. With the side-mounted HMD, none of the ambient scene is seen by the HMD eye with an occluded HMD, and with a see-through HMD, a restricted part of the ambient scene is seen by the HMD eye. Comparison of the two types of HMDs did not reveal any effect on the incidence of binocular rivalry. The choice of a visor-projected or side-mounted HMD can be made independent of binocular rivalry considerations.

HMD EYE PRESENTATION

One of the observations made during the Qualitative Laboratory Evaluation on the perceived quality of the HMD scene was eye presentation, i.e., to which eye the HMD was presented. This effect was presumed to be due to eye dominance. Eye presentation (eye dominance) was therefore tested during the screening study. The effect of eye dominance on HMD visibility was not found to be statistically significant ($p > 0.25$). A slight trend for the dominant eye to result in higher HMD visibility scores than the non-dominant eye was found. From the results of the screening study, it can be concluded that which eye the HMD is presented to is of little consequence to the incidence of binocular rivalry. Yet, the observations and comments made by individuals who have looked at and tested HMDs make us wonder.

The research conducted during the study program was directed toward HMD design parameters. The areas of training, experience, psychological set, and other non-design factors were either de-emphasized or totally excluded. Such factors could have major impact on the acceptability and operational use of HMDs and should be explored.

SCENE DYNAMICS

Static and dynamic HMD scenes were compared in the Qualitative Laboratory Evaluation. The dynamic HMD scene did not reduce the observed incidence of binocular rivalry compared to the static scene. Because of this observation and equipment limitations, scene dynamics was not investigated in the screening and parametric studies. However, in the validation study, a moving pointer was used for the ambient scene tracking task. The results of the validation study revealed that binocular rivalry did not affect the tracking task, probably because of the moving pointer. One reference was found in the literature (December, 1960) that indicated movement (scene dynamics) to play a part in binocular rivalry.

The effect of scene dynamics on binocular rivalry with HMDs, therefore, is uncertain. A dynamic HMD scene, whether sensor video or symbology, may make the HMD more predominant, but to what extent is unknown.

SCENE COMPLEXITY

High and low complexity ambient scenes were investigated in the screening study. This parameter had the single greatest effect on HMD scene visibility, accounting for 26 percent of the study variance. When the HMD scene was seen against a low complexity ambient scene, HMD scene visibility was 86 percent (averaged across the other remaining 11 parameters). When the HMD scene was seen against a high complexity ambient scene, HMD scene visibility was 55 percent. The inherent relative contour strength of the HMD and ambient scenes is a major determiner of which scene will predominate.

There are two methods which can be used to control the relative complexity of the HMD and ambient scenes. The operator could position his head such that the scene he wants to see is against a low complexity area of the other scene. This solution is undesirable, because a pilot would not want to be restricted to where he looks. It is also unworkable when under g loading. The second method is a bifocular HMD. With the bifocular HMD, the center of the HMD is located below the horizontal line of sight. Thus when the operator attends to the ambient scene (the cockpit instruments or out the windscreen) the HMD is not in the line of sight of either eye and binocular conflict is prevented. To view the HMD, the operator shifts his eyes downward. Since the ambient scene perceived by the ambient eye which results from the angle of view is of a dark, low complexity cockpit area, binocular conflict with the HMD image is greatly reduced.

The validation study demonstrated that with a bifocular HMD configuration binocular rivalry is virtually eliminated. In that study, the bifocular HMD produced results equivalent to a control condition in which no ambient scene was present.

In summary, the research conducted indicates that the luminance and complexity of the HMD and ambient scenes are the key parameters which determine the incidence of binocular rivalry and scene predominance. Design parameters which influence HMD and ambient luminance should be established for their joint effects on HMD image quality task requirements and binocular rivalry.

HMD resolution and contrast are of secondary importance to binocular rivalry effects on HMD predominance. Resolution and contrast requirements should be based on HMD image quality and operator task requirements.

HMD field of view, color, framing, and accommodation have negligible effects on controlling binocular rivalry. Therefore, specification of these parameters for HMD design can be made independent of considerations of binocular rivalry.

The influence of scene dynamics and eye dominance on binocular rivalry is uncertain. Additional research on these two parameters as well as psychological factors, such as, training, experience, and operator task set is recommended.

SECTION 5

IMAGE QUALITY ANALYSIS

INTRODUCTION

The image source of the helmet-mounted display (HMD) is not viewed directly as in the case of conventional panel-mounted displays, rather it is viewed through a series of optics and combining glass to form a virtual image. The transmittance of the combining glass can be designed either to occlude the external ambient or to be see-through, allowing the eye to view the HMD image source and external scene simultaneously. Although there are operational advantages of see-through displays, there is a degradation in image quality when two or more images are combined. If one considers the light intensity modulation from the image source as the signal and extraneous light from the external scene as unwanted signal (i. e., noise), then the signal-to-noise ratio will decrease with increasing combiner transparency. The effect is to decrease display modulation and reduce the useful number of shades of gray. Acceptable compromises can be attained by appropriate selection of the combining glass transmittance. The analysis presented in this section relates the effects of various combinations of combining glass transparency, image source brightness, and external ambient on HMD image quality.

The quality of image forming displays can be characterised by gray scale rendition, edge sharpness, display resolution, and display uniformity. Additional factors affecting subjective quality include ambient light incident on the display, mismatch between the display brightness and area surrounding the display, and characteristics of the eye. A convenient index of image quality utilizes the concept of the modulation transfer function (MTF). The MTF describes how modulation or contrast varies as a function of spatial frequency and relates system sine wave responses to zero frequency or large area transfer.

MTFs are particularly useful in analysing the combined effects of several elements in the system by multiplying the MTFs of the individual elements to predict the total system performance. Direct comparison of the MTF curves can provide a qualitative measure of system performance.

For comparison purposes and trade-off analysis, the MTF curves can be quantified by a single numerical quantity, such as spatial frequency for a specified modulation response (i. e., conventional definition of resolution) or equivalent bandpass which is derived from the area under the MTF curve. Another useful measure is the eye limiting resolution, which can be found by plotting the visual response of the eye along with the MTF of the display. The intercept of the two curves represents the eye limiting response. The area bounded by the two curves represents the useful modulation that can be resolved by the eye. Any signal below the eye curve or to the right of the intercept between the two curves cannot be resolved by the eye.

Plotting the eye response against the MTF of the display permits the calculation of another single measure of display quality, the Modulation Transfer Function Area (MTFA). This value is similar to Shade's Ne, in that it represents the area under the MTF curve. The MTFA is bounded by the MTF of the display and the visual demand curve of the eye as illustrated by the shaded area of Figure 35. The MTFA concept was first introduced by Charman and Olin (1965) as a photographic metric, designated as the Threshold Quality Factor and subsequently renamed MTFA by Borough, Follis, Warnock, and Britt (1967).

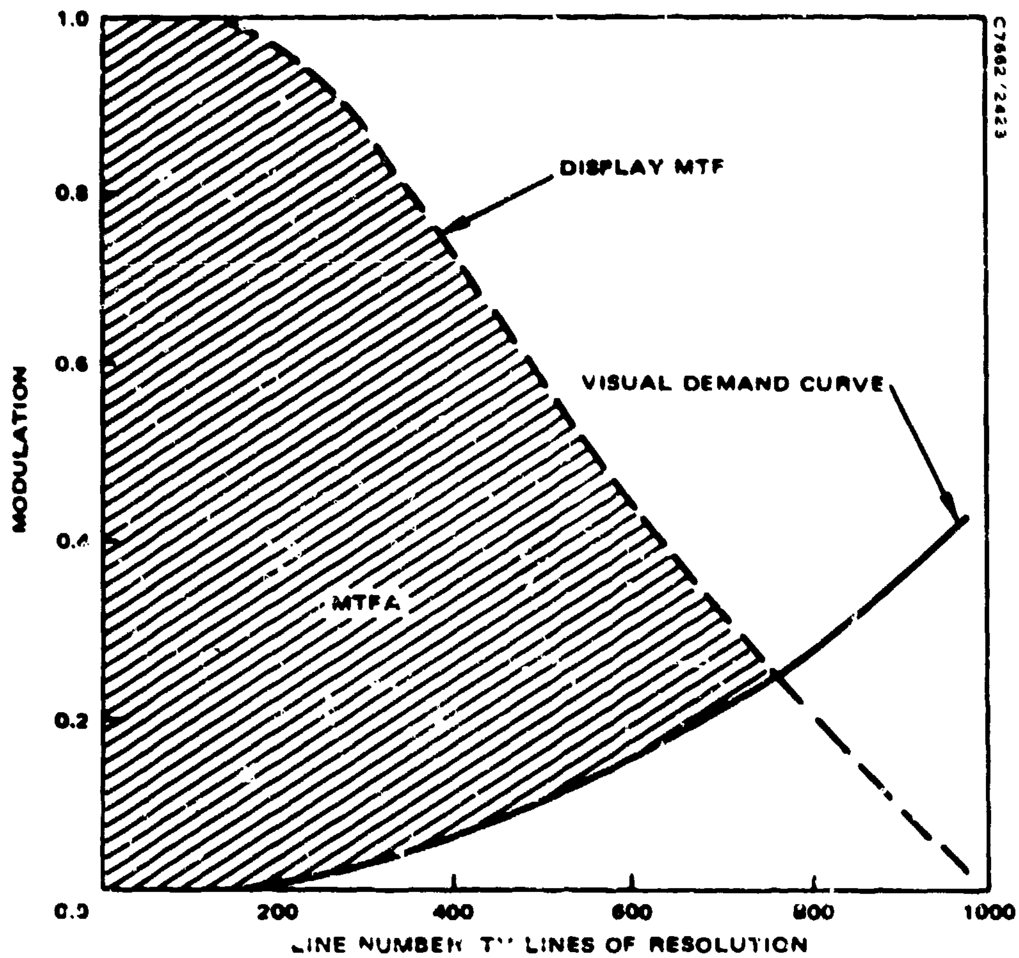


Figure 35. Representation of MTI' concepts.

Two studies have been made to date relating MTFA to image quality. The first study (Borough, Follis, Warnock, and Britt, 1967) compared the subjective image quality rating of 36 trained observers, judging 288 transparencies representing 32 levels of MTFA. A correlation of 0.92 was found between subjective image quality ratings and MTFA. The second study (Klingberg, Elworth, and Filleau, 1970) investigated the relationship between MTFA and information extraction of 384 trained military photo-interpreters. A correlation of 0.93 was found between MTFA and information extraction. More recently Synder (1973) has proposed extending the MTFA metric to raster scan displays and has conducted a series of laboratory experiments relating operator performance with the MTFA of raster-scan displays. Synder concludes that although MTFA is an excellent metric for judging overall image quality and for selecting the best imaging system for a broad range of applications, it is a poor predictor of typical observer performance in recognizing a specific target for a specific set of conditions.

VARIABLES IN THE ANALYSIS

The variables included in the image quality analysis are listed in Table 17.

TABLE 17. VARIABLES IN THE ANALYSIS

Variables	Levels
Ambient Luminance	500, 1000, 2000, and 4000 foot lamberts
Average Display Luminance	50, 100, 500, and 1000 foot lamberts
Combiner Transparency (see-through)	0.0, 0.1, 1.0, and 10 percent
Angular Subtense of Display	15, 30, and 45 degrees

VISUAL RESPONSE CURVES

The visual response curves used in the analysis were adapted from psychophysical research conducted at Hughes Aircraft Company which included the effects caused by: the angle subtended by the image source, the luminance mismatch between the image source and area surrounding the display, the display luminance, and the ambient luminance. The empirical threshold visual data were analyzed by a stepwise multiple regression yielding an equation relating visual modulation threshold (M) to the parameters of stimulus luminance (A), surrounding luminance (B), stimulus subtense (C), and spatial frequency (D) as follows:

$$
\begin{aligned}
\log M = \; & -0.3180 \log A + 0.12219 \log B - 1.62162 \log C \\
& - 3.05375 \log D + 0.1504 (\log A)^2 \\
& + 0.10692 (\log B)^2 + 0.02441 (\log C)^2 \\
& + 2.26564 (\log D)^2 - 0.19435 \log A \log B \\
& - 0.01115 \log A \log C - 0.16251 \log A \log D \\
& - 0.10949 \log B \log C - 0.03871 \log C \log D \\
& + 1.24461 \log C \log D - 0.8112,
\end{aligned}
\qquad (1)
$$

where spatial frequency is in cycles/degree, luminance is in foot-lamberts, and subtense is in degrees. The equation yields thresholds which were obtained by the "adjustment method" which are numerically equivalent to 90 percent thresholds. The psychophysical tests, from which this equation was derived, also included values representing "comfort" modulations which were found to be 1.6 times larger than the threshold values. The visual response curves shown in the accompanying figures were derived by multiplying the modulation thresholds obtained from equation (1) by a field-factor of 1.6.

MTF CURVE TRANSFORMATION

The effect of ambient scene luminance on see-through virtual image displays is to add a light bias to the displayed image, thereby reducing contrast in accordance with the expression

$$M_E = \frac{M_o}{1 + \frac{B\ additive}{B\ average}}, \qquad (2)$$

where M_E is the effective modulation, M_o is the inherent modulation of the displayed image, B average is the average luminance of the displayed image without ambient luminance. B additive is the luminance seen by the observer on the display due to the ambient.

The inherent modulation M_o was derived by the equation

$$M_o = e^{-2(\pi \sigma N)^2},$$

where the inherent modulation M_0 is the display response to a sine wave input, a is the radius of the 60 percent amplitude spot width, and N is the sine wave spatial frequency in cycles/unit distance. The MTF curves developed from this expression are valid, providing the luminous intensity of the spot has a gaussian distribution. For the purpose of this study, the following assumptions were made with regard to the relationship between display luminance and resolution:

Display Luminance foot-lamberts	TV Limiting Resolution, lines per display width
50	800
100	700
500	500
1000	400

DYNAMIC RANGE AND GRAY LEVELS

Given the corrected image modulation, the dynamic range of the corrected displayed image is provided by the expression

$$RE = \frac{ME + 1}{1 - ME} . \tag{3}$$

The number of display gray shades (G_s) can be calculated, if one assumes that a gray level constitutes a change in luminance in steps of $\sqrt{2}$, by

$$G_s = \frac{2 \log RE}{\log 2} + 1. \tag{4}$$

RESULTS OF THE ANALYSIS

The effects on M_E and visual response of display luminance, ambient luminance, display combiner transparency, and angular subtense of the display are shown graphically in computer generated curves in Figures 36 through 47. These 12 graphs represent different combinations of ambient luminance and display transparency. Each figure contains M_E curves for display luminances of 50, 100, 500, and 1000 foot-lamberts. Three sets of visual response curves are plotted for viewing subtenses of 15, 30, and 45 degrees. The four curves within each set relate to the four display luminances.

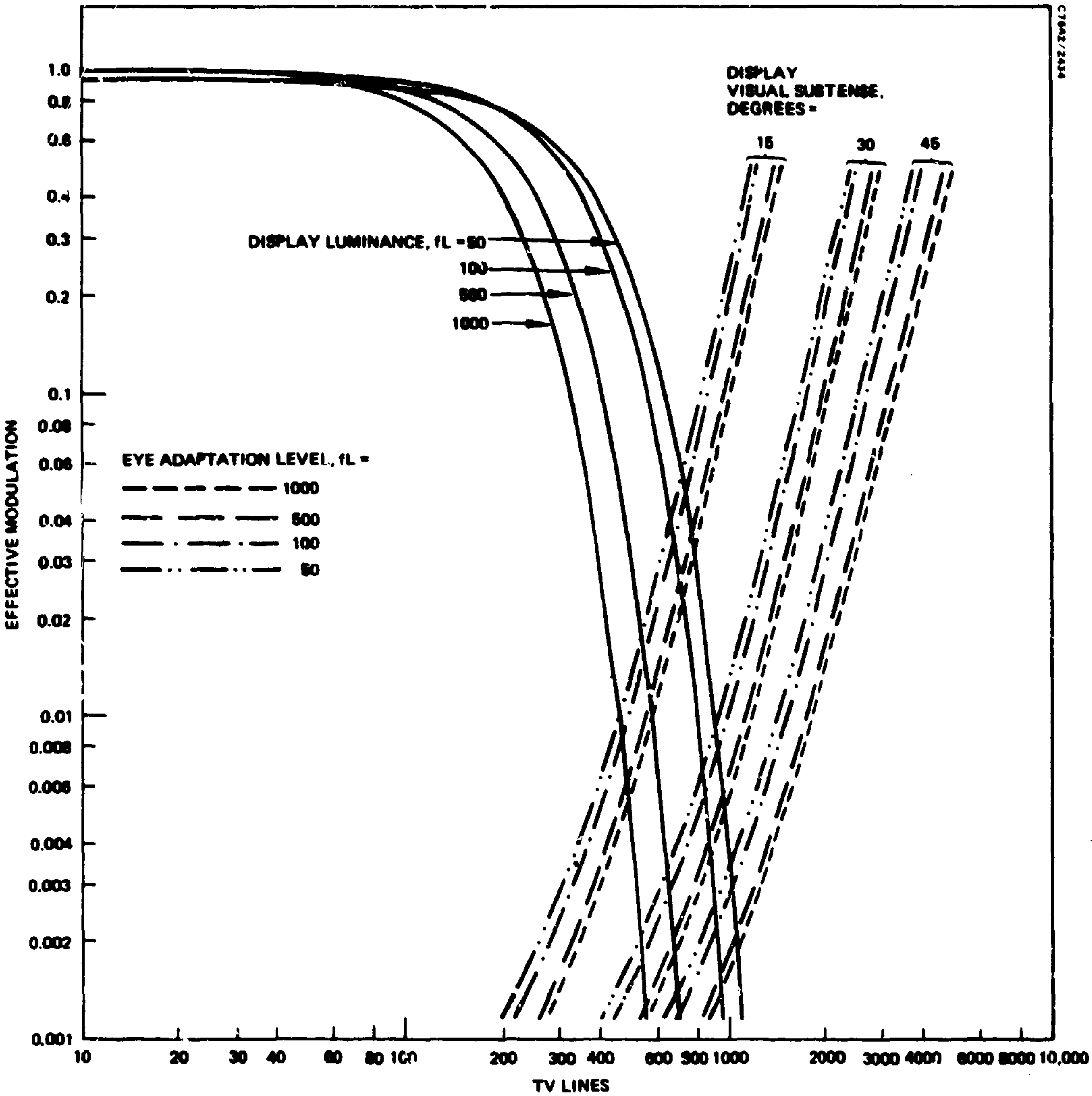


Figure 36. Modulation transfer function and visual acuity threshold for 0.1-percent transmittance see-through display and 4000-foot lambert ambient.

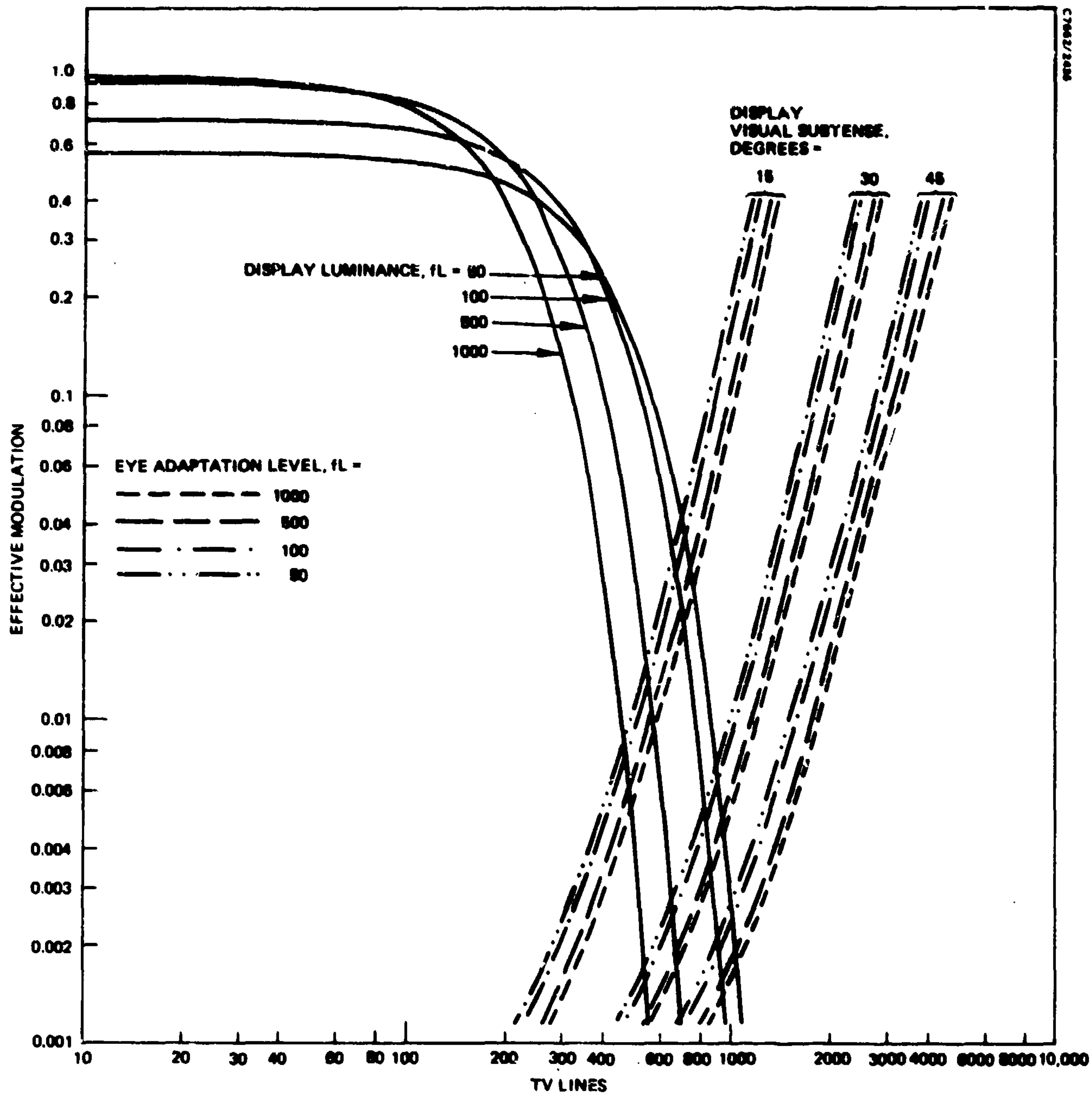


Figure 37. Modulation transfer function and visual acuity threshold for 1.0-percent transmittance see-through display and 4000-foot lambert ambient.

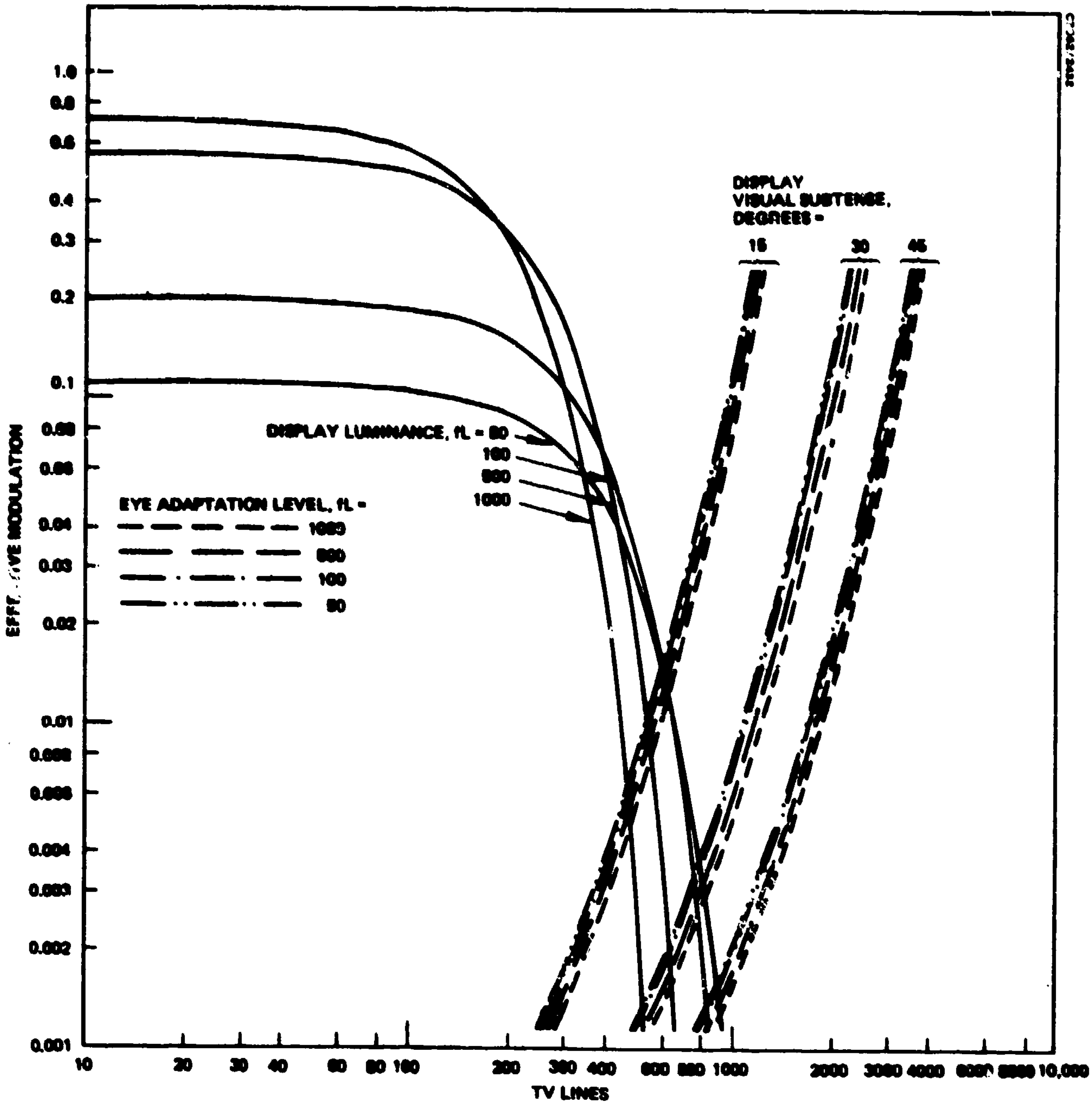


Figure 38. Modulation transfer function and visual acuity threshold for 10.0-percent transmittance see-through display and 4000-foot lambert ambient.

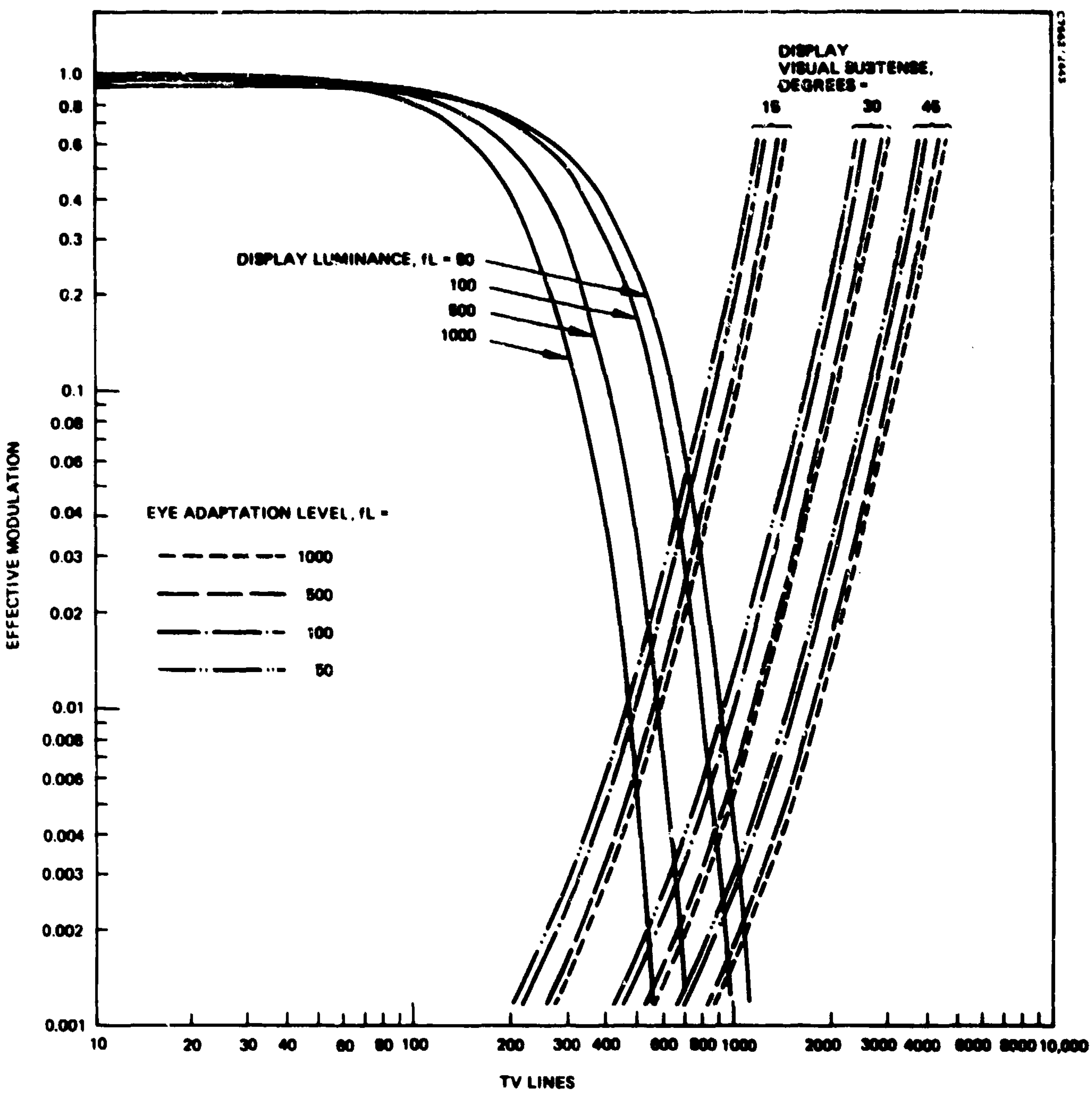


Figure 39. Modulation transfer function and visual acuity threshold for 0.1-percent transmittance see-through display and 2000-foot lambert ambient.

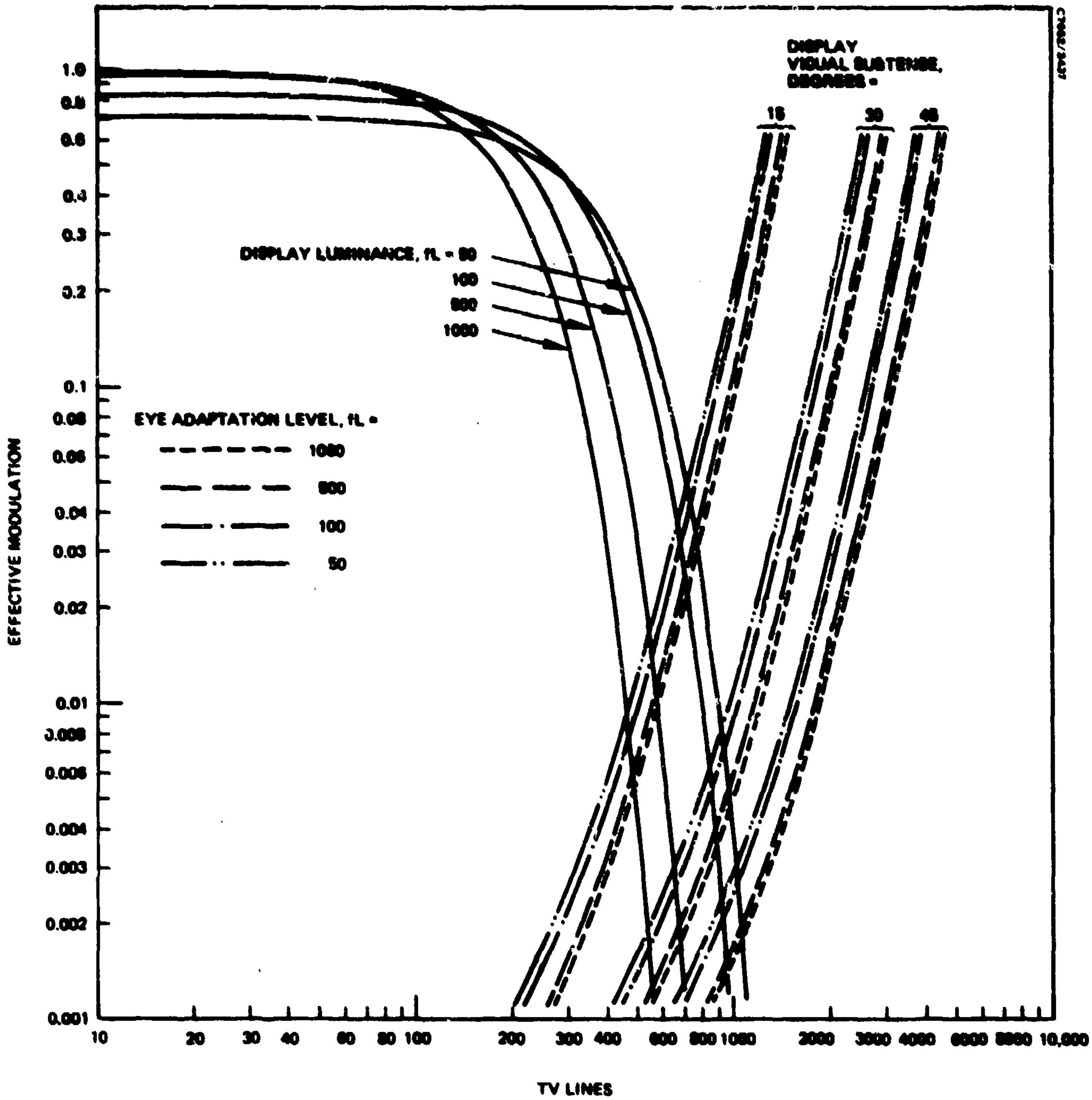


Figure 40. Modulation transfer function and visual acuity threshold for 1.0-percent transmittance see-through display and 2000-foot lambert ambient.

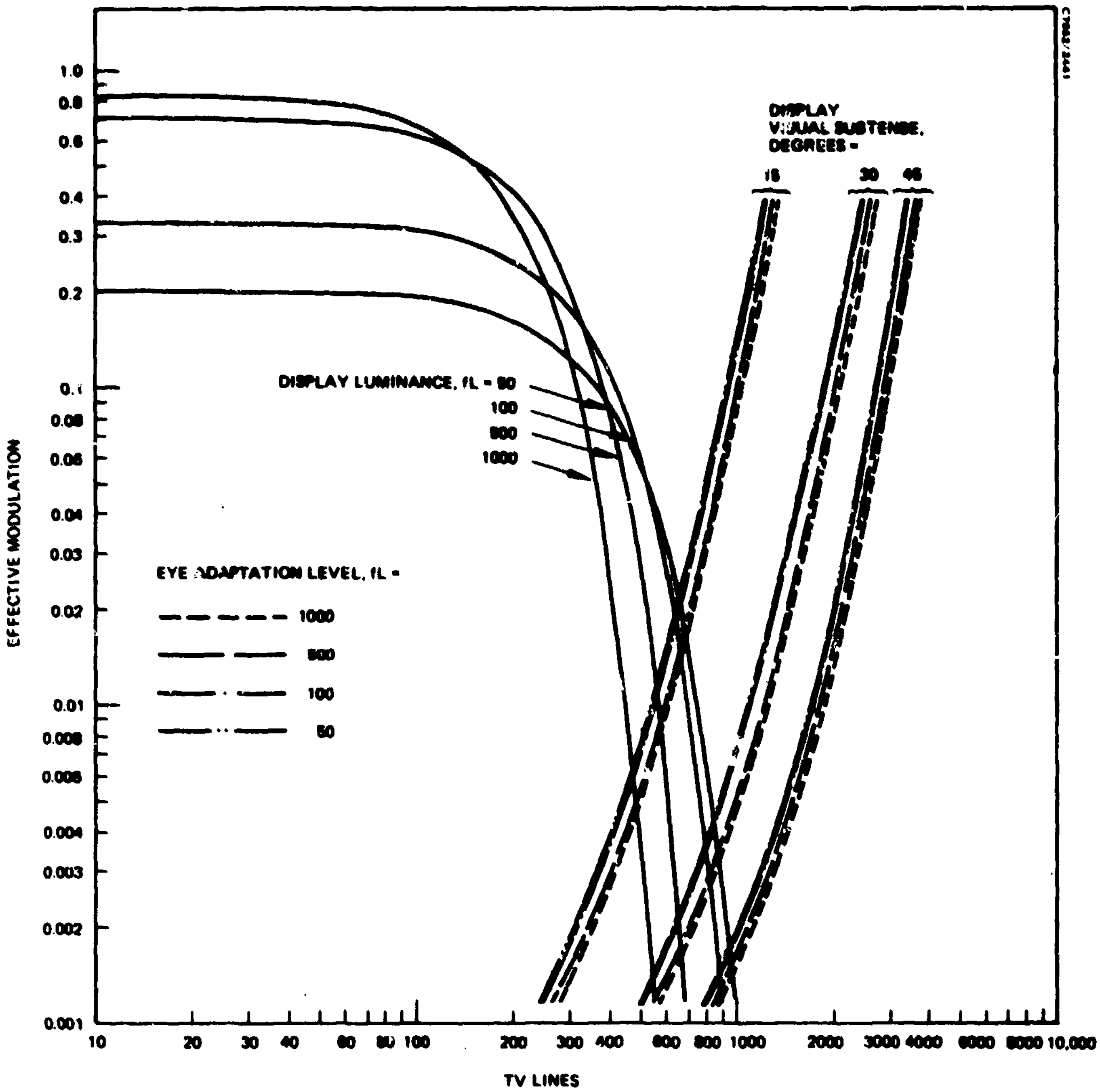


Figure 41. Modulation transfer function and visual acuity threshold for 10.0-percent transmittance see-through display and 2000-foot lambert ambient.

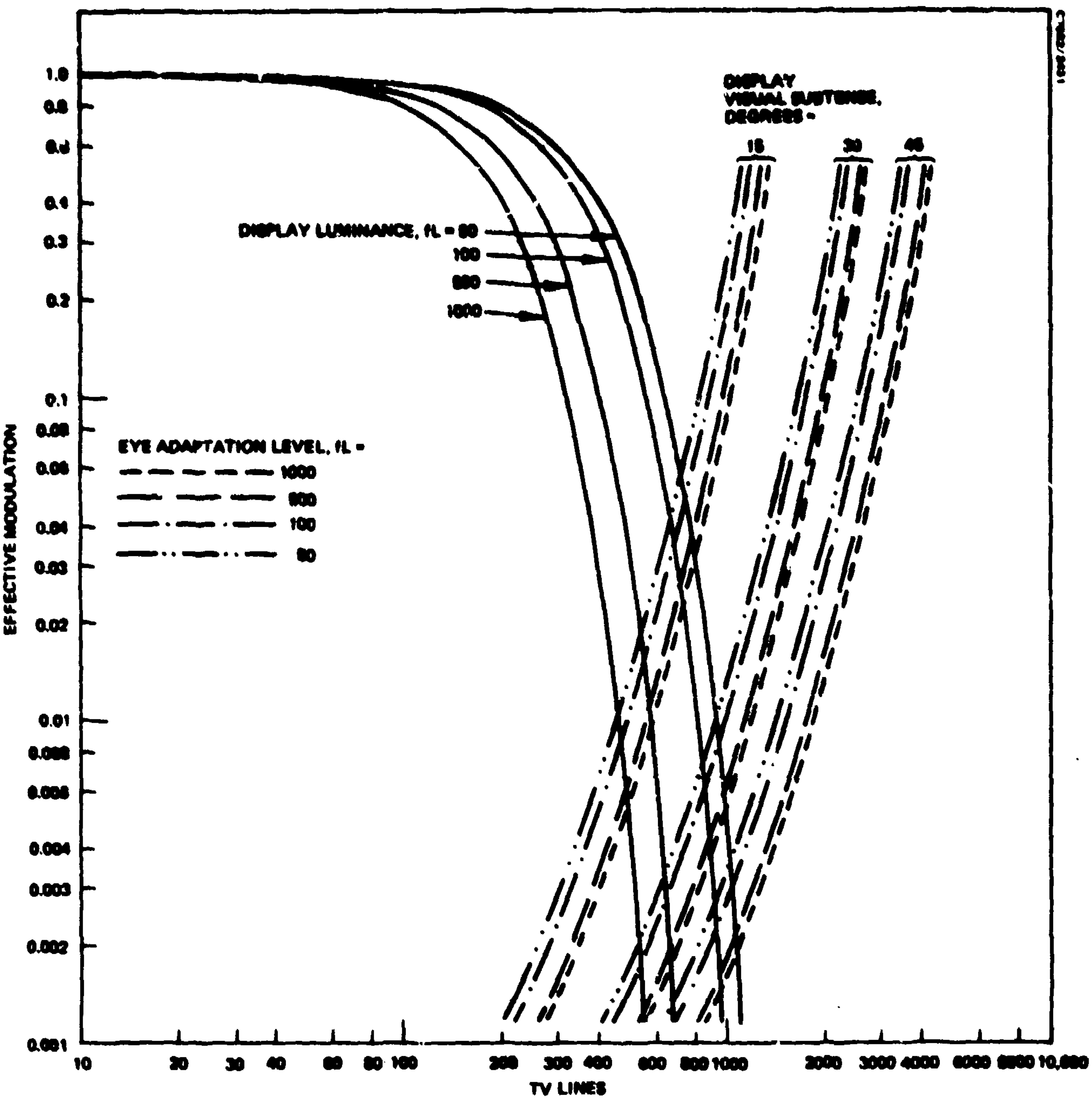


Figure 42. Modulation transfer function and visual acuity threshold for 0.1-percent transmittance see-through display and 1000-foot lambert ambient.

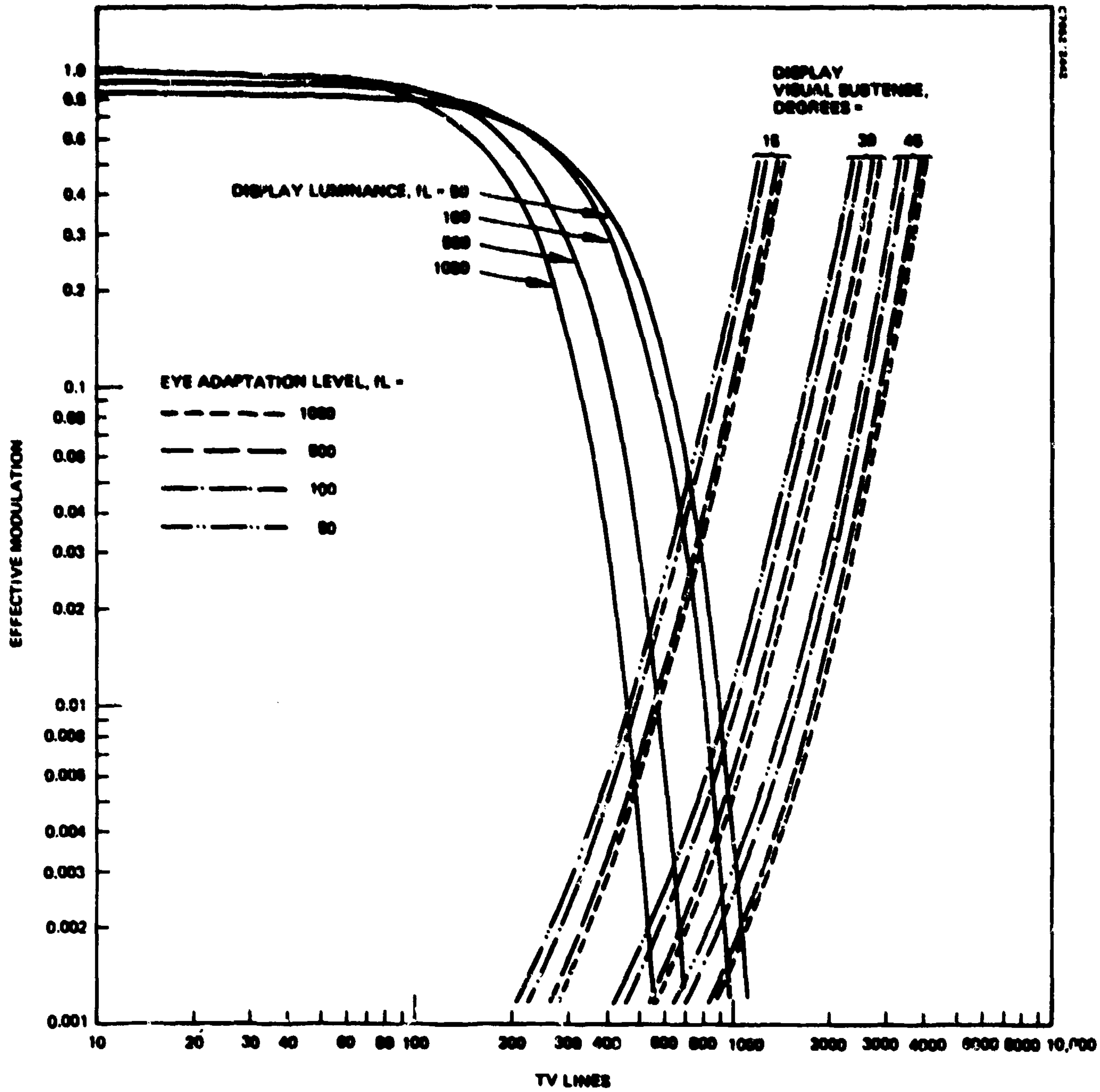


Figure 43. Modulation transfer function and visual acuity threshold for 1.0-percent transmittance see-through display and 1000-foot lambert ambient.

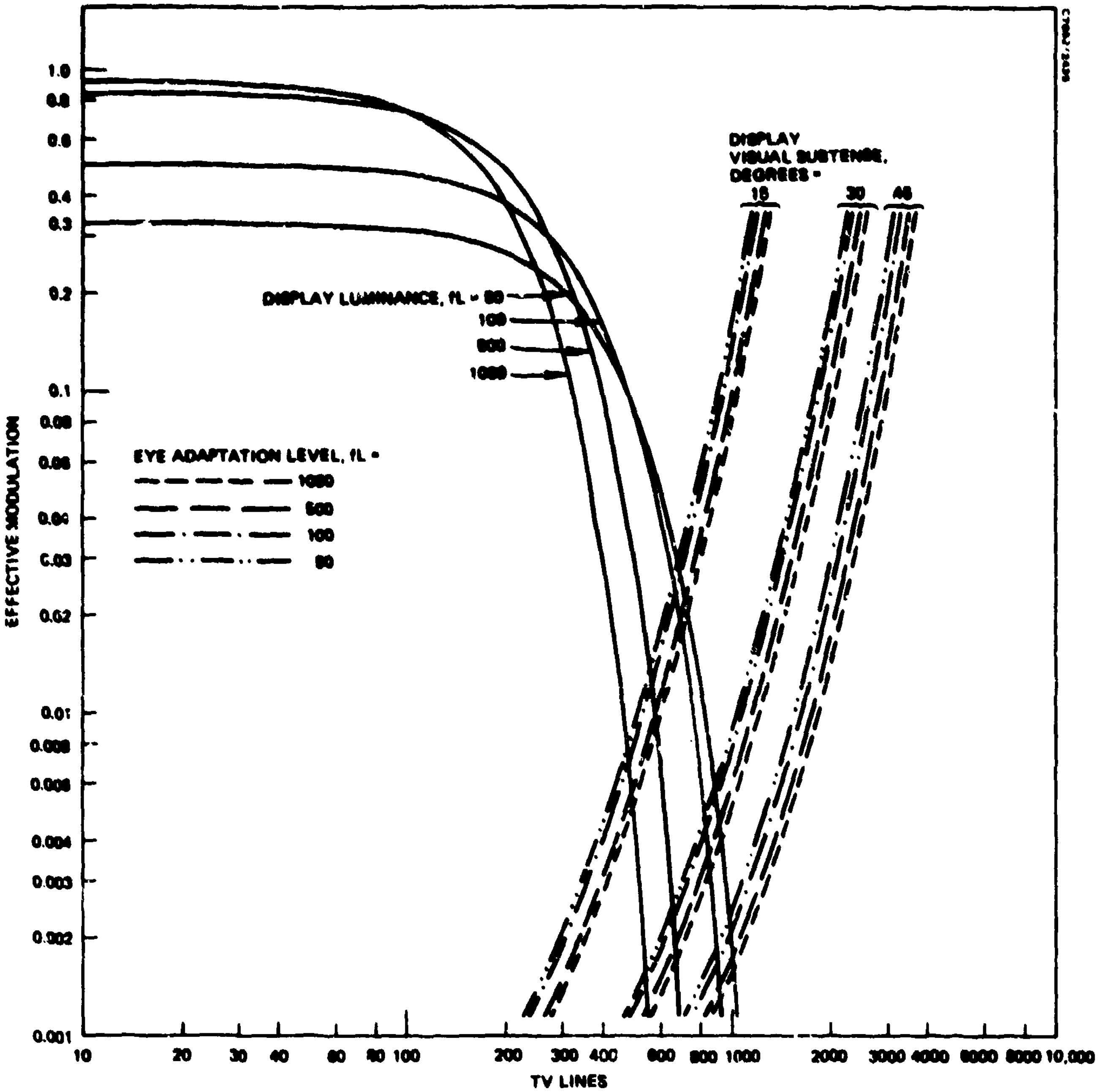


Figure 44, Modulation transfer function and visual acuity threshold for 10.0-percent transmittance see-through display and 1000-foot lambert ambient.

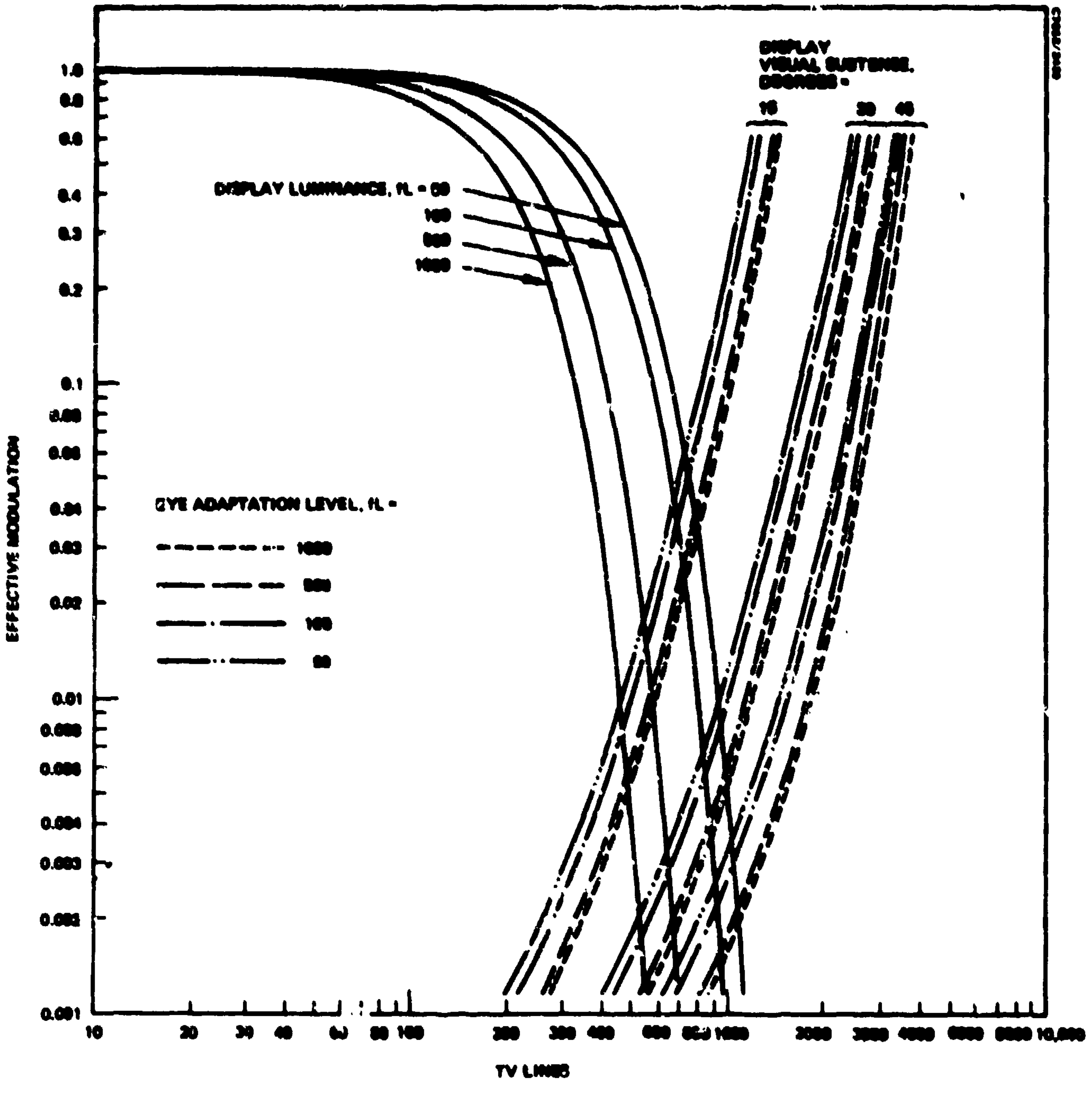


Figure 45. Modulation transfer function and visual acuity threshold for 0.1-percent transmittance see-through display and 500-foot lambert ambient.

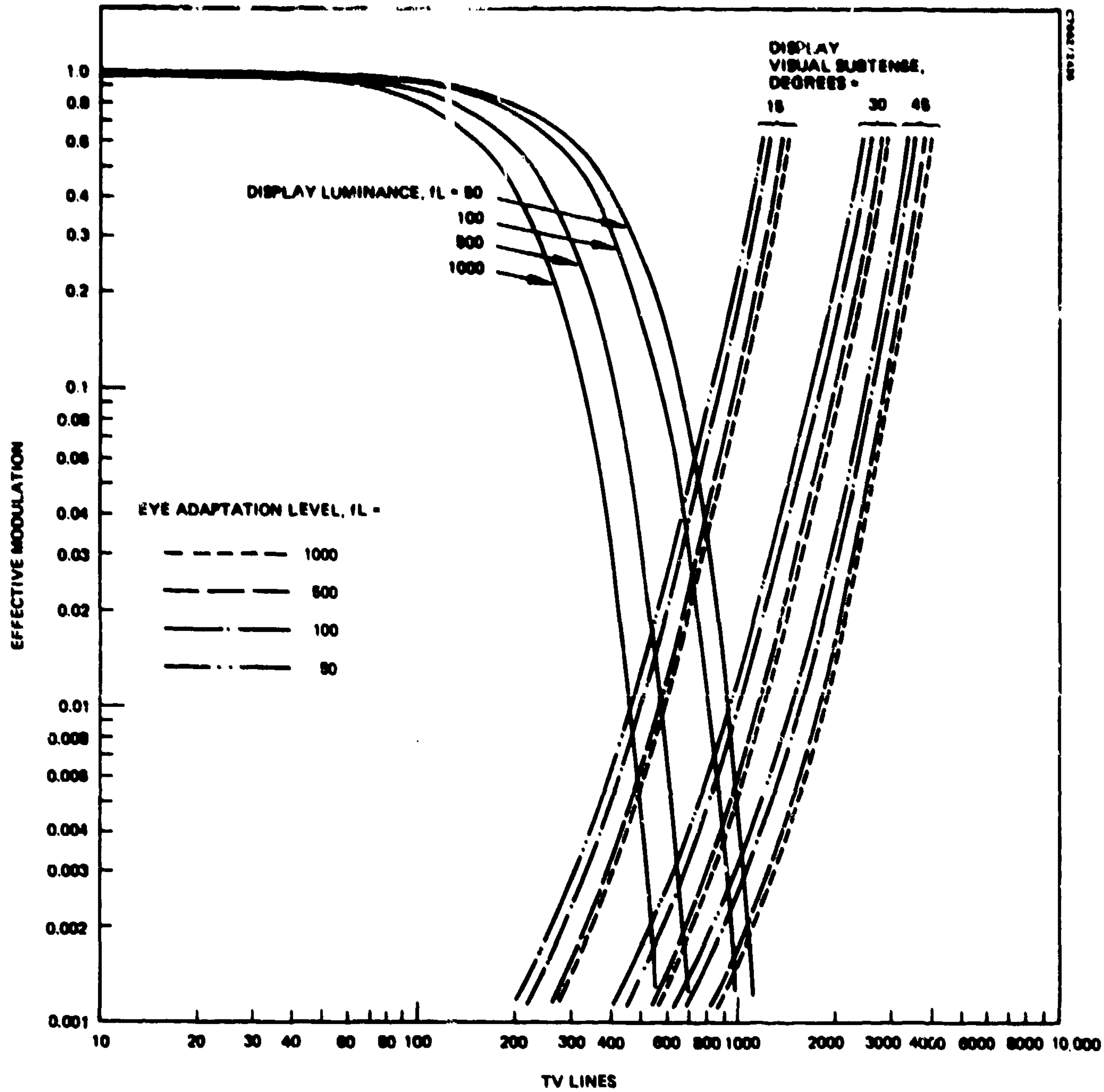


Figure 46. Modulation transfer function and visual acuity threshold for 1.0-percent transmittance see-through display and 500-foot lambert ambient.

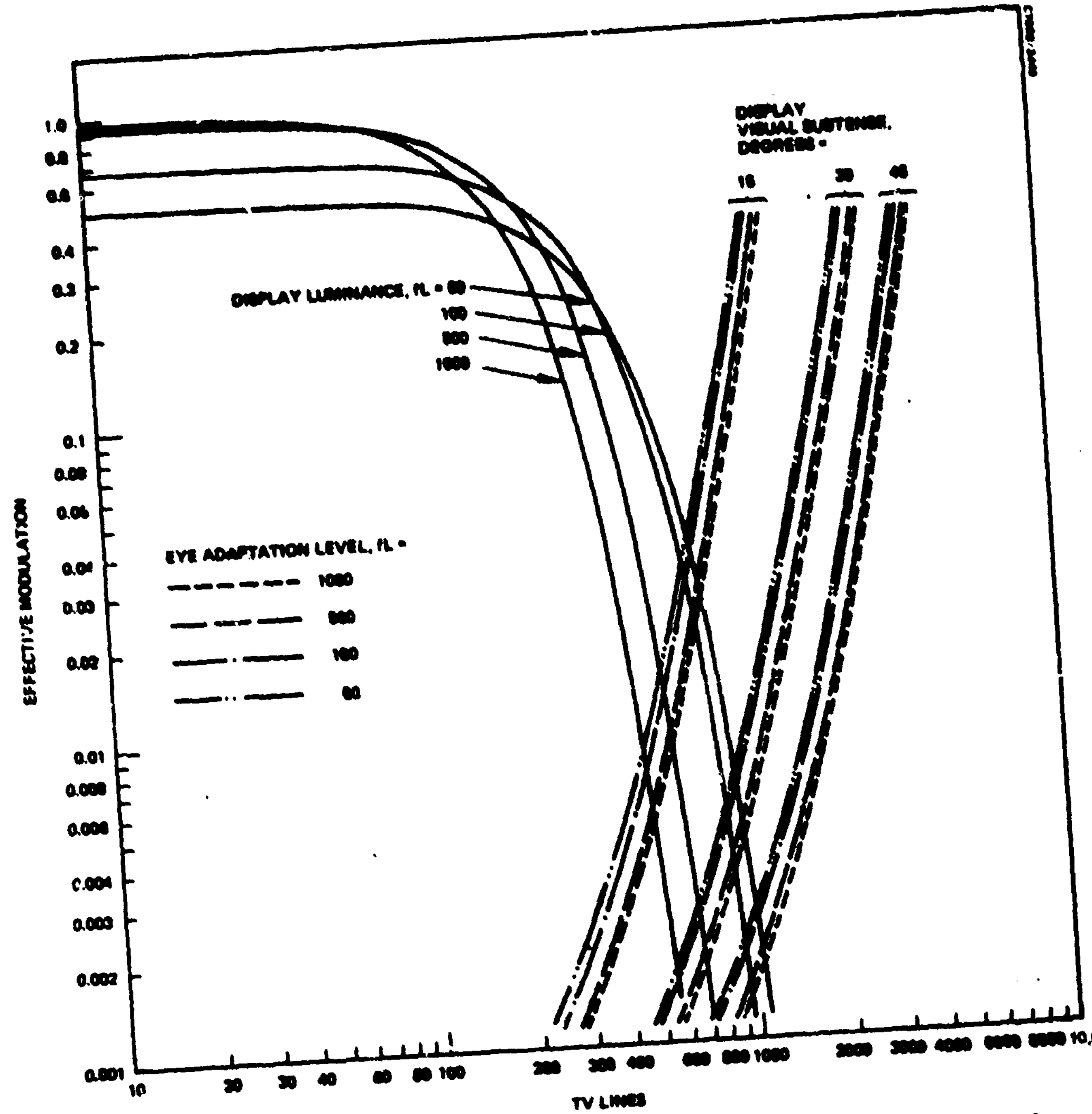


Figure 47. Modulation transfer function and visual acuity threshold for 10.0-percent transmittance see-through display and 500-foot lambert ambient.

From inspection of Figure 36 through 47, it can be seen that eye limiting resolution increases with increasing display subtense. For example, in Figure 36 (which is for a 4000-foot candle ambient in combination with a 0.1-percent display see-through), a 50-fL display has an eye limiting resolution of 718 TV lines across the display when the angular subtense is 45 degrees. It can also be observed that the lower luminance displays have higher resolution. The later is characteristic of cathode ray tubes. Display brightness is increased by increasing beam current which causes a growth in spot size and hence a reduction in display resolution.

Comparing Figure 36 with Figure 38, the effect of combiner glass transparencies of 0.1 and 10 percent, respectively, can be seen. A 50-fL display viewed in a 4000-foot lambert ambient with a 0.1-percent transparency combiner yields 93 percent of its inherent modulation. The same display in the same ambient with a 10-percent transmission combiner yields only 11 percent of its inherent modulation.

Figure 48 illustrates the effect of display luminance and visual subtense on occluded displays. For all practical purposes, there is no difference between an occluded display and a 0.1 percent see-through display.

The results shown in Figures 37 through 48 are presented in tabular form in Table II which includes: display dynamic range, number of gray shades, visual cutoff frequency, modulation at cutoff frequency, and MTFA for each of the combinations of variables addressed in the analysis.

Figure 49 is a replot of the data in Table 18, illustrating the effect of display luminance variation. The latter has little effect on visual cutoff frequency (eye limiting resolution) for 0.1- and 1.0-percent filter transparencies, while a noticeable degradation is evident for a 10-percent transparency.

Figure 49 also shows the relationship between visual cutoff frequency and angular subtense of the display. A large increase in visual cutoff frequency occurred as the angular display subtense increased from 15 degrees to 45 degrees. This increase is somewhat misleading in that the higher cutoff frequencies attained with the 30- and 45-degree viewing angles are achieved at very low modulation levels. Consider the 50-fL, 0.1-percent transparency display shown in Figure 47. While the visual cutoff frequency increased from 718 to 1006 TV lines as the angular subtense increased from 15- to 45-degrees, the corresponding modulation decreased from 5.4 to 0.3 percent. It is doubtful that modulations below 1 or 2 percent would have a practical effect on image quality or operator performance.

A more comprehensive unitary measure of image quality is provided by MFTA, which represents the area bounded by the visual response curve of the eye and the display MTF. The values of MTFA for various combinations of display brightness, transparency, ambient illumination, and angular subtense are given in Table 18 and summarized graphically in Figures 50, 51, and 52.

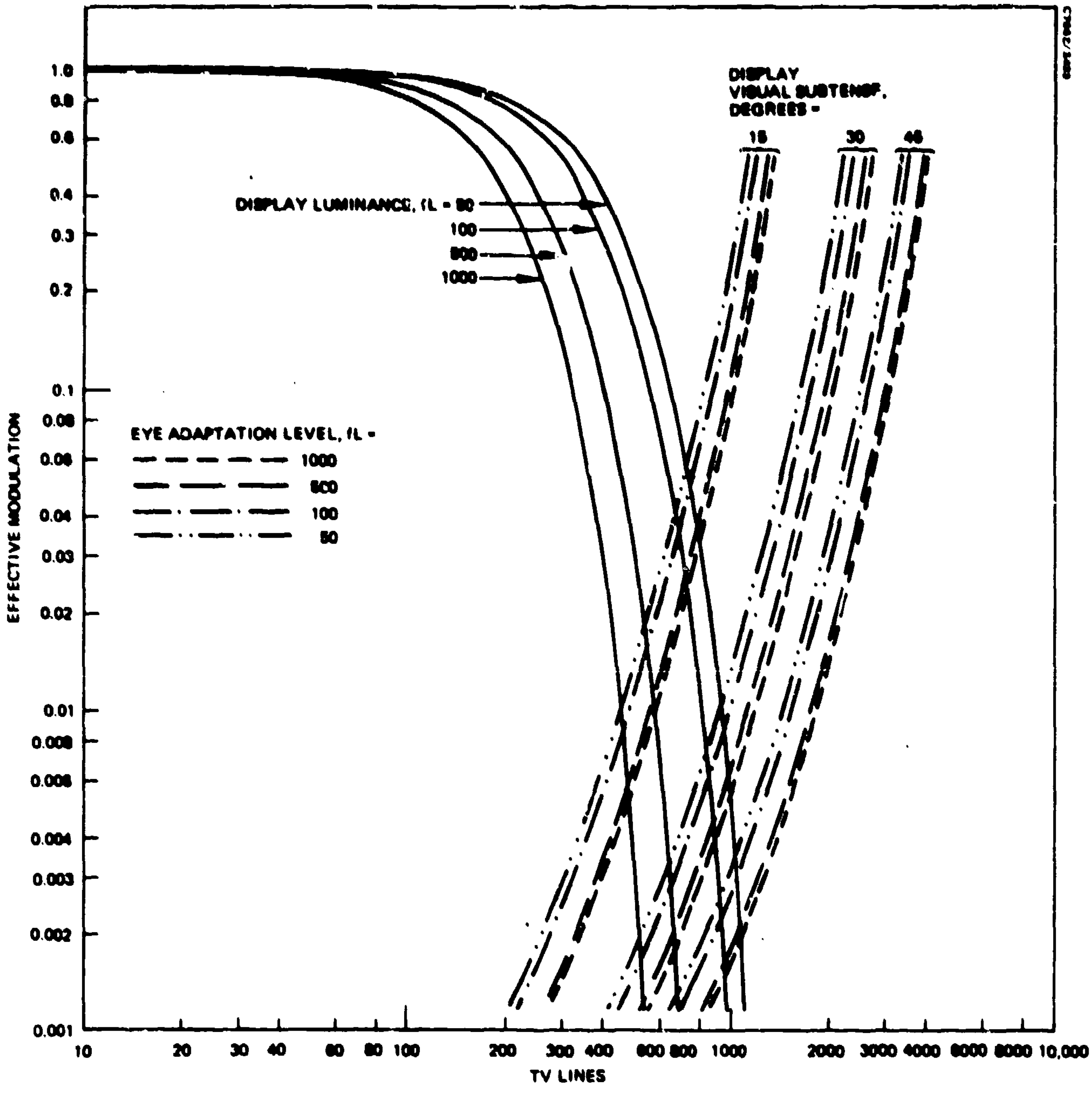


Figure 48. Modulation transfer function and visual acuity threshold for 0. 0-percent transmittance (occluded) display.

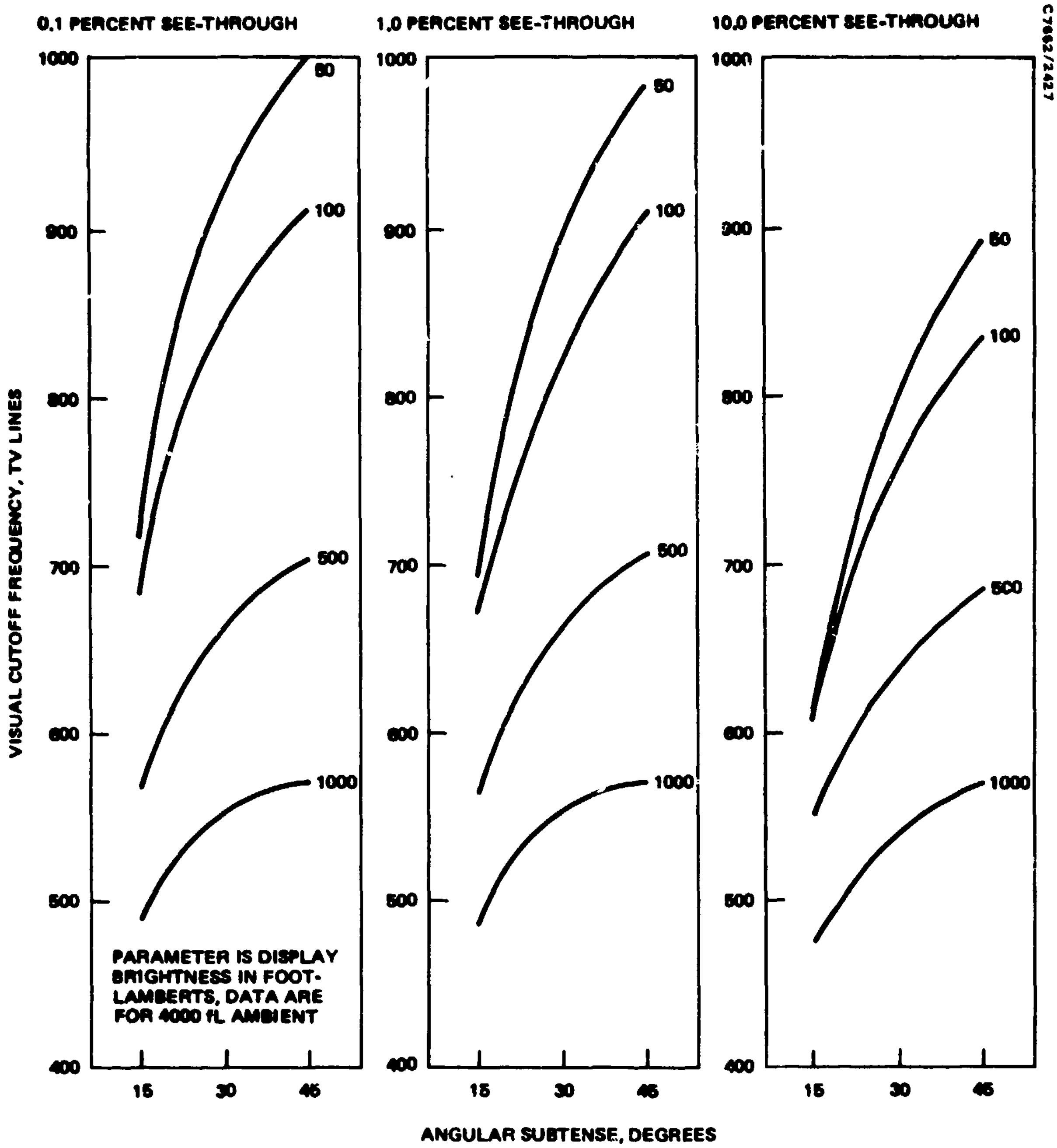


Figure 49. Visual cutoff frequency as a function of angular subtense f r 0. 1, 1. 0, and 10. 0 percent see-through.

TABLE 18. SUMMARY OF DISPLAY IMAGE QUALITY PERFORMANCE PARAMETERS AS A FUNCTION OF AMBIENT ILLUMINATION, DISPLAY LUMINANCE, AND PERCENT TRANSPARENCY

Ambient Illumination, Foot-Lamberts	Average Display Luminance, Foot-Lamberts	See-Through, Percent Transparency	Effective Modulation (M_E)	Dynamic Range (R_E)	Gray Shades
4000	1000	0.1	0.99	199	16
	500		0.99	199	16
	100		0.96	49	12
	50		0.93	26	10
2000	1000	0.1	0.99	199	16
	500		0.99	199	16
	100		0.98	99	14
	50		0.96	49	12
1000	1000	0.1	0.99	199	16
	500		0.99	199	16
	100		0.99	199	16
	50		0.98	99	14
500	1000	0.1	0.99	199	16
	500		0.99	199	16
	100		0.99	199	16
	50		0.99	199	16

Visual Cutoff Frequency, TV Lines			Modulation At Cutoff Frequency			MTFA		
Visual Subtense, Degrees			Visual Subtense, Degrees			Visual Subtense, Degrees		
15	30	45	15	30	45	15	30	45
489	553	570	0.005	0.001	0.0006	186	187	187
567	663	702	0.011	0.002	0.0008	233	235	235
682	847	911	0.035	0.006	0.002	320	326	327
718	921	1006	0.055	0.009	0.003	340	352	354
488	553	570	0.005	0.001	0.005	186	187	187
567	663	702	0.010	0.002	0.0008	233	235	235
682	847	911	0.035	0.006	0.002	316	323	324
718	921	1006	0.056	0.010	0.003	351	363	365
489	553	570	0.005	0.001	0.0005	186	187	187
567	663	702	0.011	0.002	0.0008	233	235	235
682	847	911	0.035	0.006	0.002	320	326	327
724	921	1006	0.058	0.010	0.003	359	371	373
489	553	570	0.005	0.001	0.0005	186	187	187
567	663	702	0.011	0.002	0.0008	233	235	235
682	847	911	0.035	0.006	0.002	320	326	327
724	921	1006	0.058	0.010	0.003	362	374	376

Ambient Illumination, Foot-Lamberts	Average Display Luminance, Foot-Lamberts	See-Through, Percent Transparency	Effective Modulation (M_E)	Dynamic Range (R_E)	Gray Shades
4000	1000	1.0	0.96	49	12
	500		0.93	26	10
	100		0.71	5.9	6
	50		0.56	3.5	4
2000	1000	1.0	0.98	99	14
	500		0.96	49	12
	100		0.83	10.8	7
	50		0.71	5.9	6
1000	1000	1.0	0.99	199	16
	500		0.98	99	14
	100		0.91	21	9
	50		0.83	10.8	7
500	1000	1.0	0.99	199	16
	500		0.99	199	16
	100		0.95	39	11
	50		0.91	21	9

(Table 18 continued)

Visual Cutoff Frequency, TV Lines			Modulation At Cutoff Frequency			MTFA		
Visual Subtense, Degrees			Visual Subtense, Degrees			Visual Subtense, Degrees		
15	30	45	15	30	45	15	30	45
483	553	570	0.005	0.001	0.0005	180	181	181
567	663	702	0.010	0.002	0.0008	219	221	221
670	823	911	0.029	0.005	0.002	228	234	235
694	897	987	0.039	0.007	0.003	203	211	213
489	553	570	0.005	0.001	0.0005	184	185	185
567	663	702	0.010	0.002	0.0008	226	228	228
676	835	911	0.032	0.005	0.002	268	274	274
706	909	1006	0.046	0.008	0.003	258	268	270
489	553	570	0.005	0.001	0.0006	186	187	187
567	663	702	0.011	0.002	0.0008	231	232	232
676	835	911	0.033	0.005	0.002	294	300	301
712	909	1006	0.051	0.009	0.003	303	314	316
489	553	570	0.005	0.001	0.0006	186	187	187
567	663	702	0.011	0.002	0.0008	233	235	235
682	847	911	0.035	0.006	0.002	307	313	314
718	921	1006	0.054	0.009	0.003	333	344	346

Ambient Illumination, Foot-Lamberts	Average Display Luminance, Foot-Lamberts	See-Through, Percent Transparency	Effective Modulation (M_E)	Dynamic Range (R_E)	Gray Shades
4000	1000	10.0	0.71	5.9	6
	500		0.56	3.5	4
	100		0.20	1.5	2
	50		0.11	1.2	1
2000	1000	10.0	0.83	10.8	7
	500		0.71	5.9	6
	100		0.33	2.0	3
	50		0.20	1.5	1
1000	1000	10.0	0.91	21	9
	500		0.83	10.8	7
	100		0.50	3.0	4
	50		0.33	2.0	3
500	1000	10.0	0.95	39	11
	500		0.91	21	9
	100		0.67	5.1	5
	50		0.50	3.0	4

(Table 18 continued)

Visual Cutoff Frequency, TV Lines			Modulation At Cutoff Frequency			MTFA		
Visual Subtense, Degrees			Visual Subtense, Degrees			Visual Subtense, Degrees		
15	30	45	15	30	45	15	30	45
477	540	570	0.005	0.001	0.0005	133	134	134
549	639	684	0.008	0.002	0.0007	132	133	133
609	762	835	0.014	0.003	0.002	63	66	66
609	798	892	0.014	0.003	0.001	38	41	42
483	553	570	0.005	0.001	0.0005	156	156	156
555	651	684	0.009	0.002	0.0008	167	168	168
634	786	873	0.018	0.003	0.001	105	108	109
646	835	930	0.021	0.004	0.002	71	75	76
483	553	570	0.005	0.0005	0.0005	171	172	172
561	663	702	0.010	0.002	0.0008	195	197	197
652	810	892	0.023	0.004	0.002	160	164	165
670	860	949	0.028	0.005	0.002	118	124	125
483	553	570	0.005	0.001	0.0005	179	179	179
567	663	702	0.010	0.002	0.0008	214	216	216
664	823	892	0.027	0.005	0.002	215	221	222
688	884	987	0.036	0.007	0.003	181	188	190

Ambient Illumination, Foot-Lamberts	Average Display Luminance, Foot-Lamberts	See-Through, Percent Transparency	Effective Modulation (M_E)	Dynamic Range (R_E)	Gray Shades
Occluded	1000	0	0.999	199*	16
	500	0	0.999	199*	16
	100	0	0.999	199*	16
	50	0	0.999	199*	16

*Arbitrary dyr‑‑mic range limit.

(Table 18 concluded)

Visual Cutoff Frequency, TV Lines			Modulation At Cutoff Frequency			MTFA		
Visual Subtense, Degrees			Visual Subtense, Degrees			Visual Subtense, Degrees		
15	30	45	15	30	45	15	30	45
483	553	570	0.005	0.001	0.0005	180	181	181
567	663	702	0.011	0.002	0.0008	236	237	237
682	847	911	0.035	0.006	0.002	323	330	330
724	921	1025	0.058	0.010	0.004	366	378	380

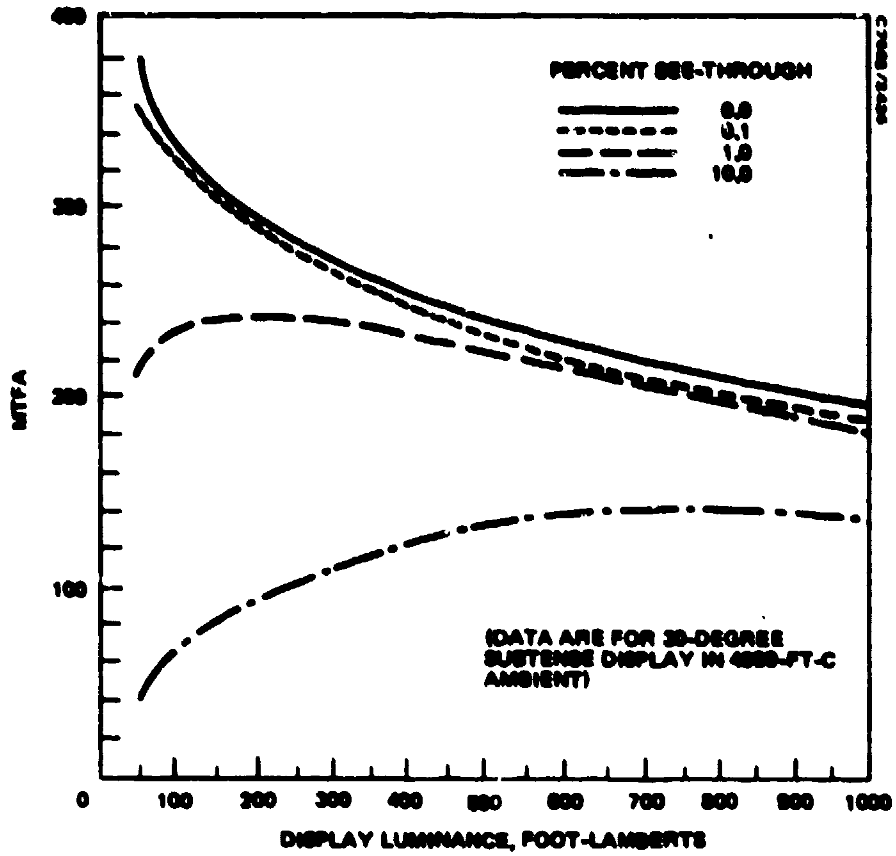


Figure 50. MTFA as a function of display luminance and percent see-through.

Figure 50 shows that MTFA improves (increases) as percent see-through decreases, and the improvement in MTFA is less sensitive to decreased percent see-through as display luminance increases. At the 0.0- and 0.1 percent see-throughs, MTFA decreased as display luminance increased from 50 to 1000 fL. At the 1.0-percent see-through, MTFA showed a small increase between 50 and 100 fL and then decreased gradually from 100 to 1000 fL. MTFA increased as display luminance increased from 50 to 500 fL at 10.0 percent see-through and then remained constant between 500 and 1000 fL. These seemingly contradictory effects of display luminance and percent see-through on MTFA are due to the counteracting influences of these two parameters on display MTF and visual response. For example, increased display luminance improves visual response and display modulation, but it decreases the display spatial frequency, because display spot size increases as display luminance is increased.

In Figure 51, increasing ambient illumination is shown to reduce MTFA. As one would expect, the effect of ambient illumination on MTFA becomes smaller as display luminance increases. Thus, at a 1000-fL display luminance there is practically no difference in MTFA for ambients ranging from 500 to 4000 fL.

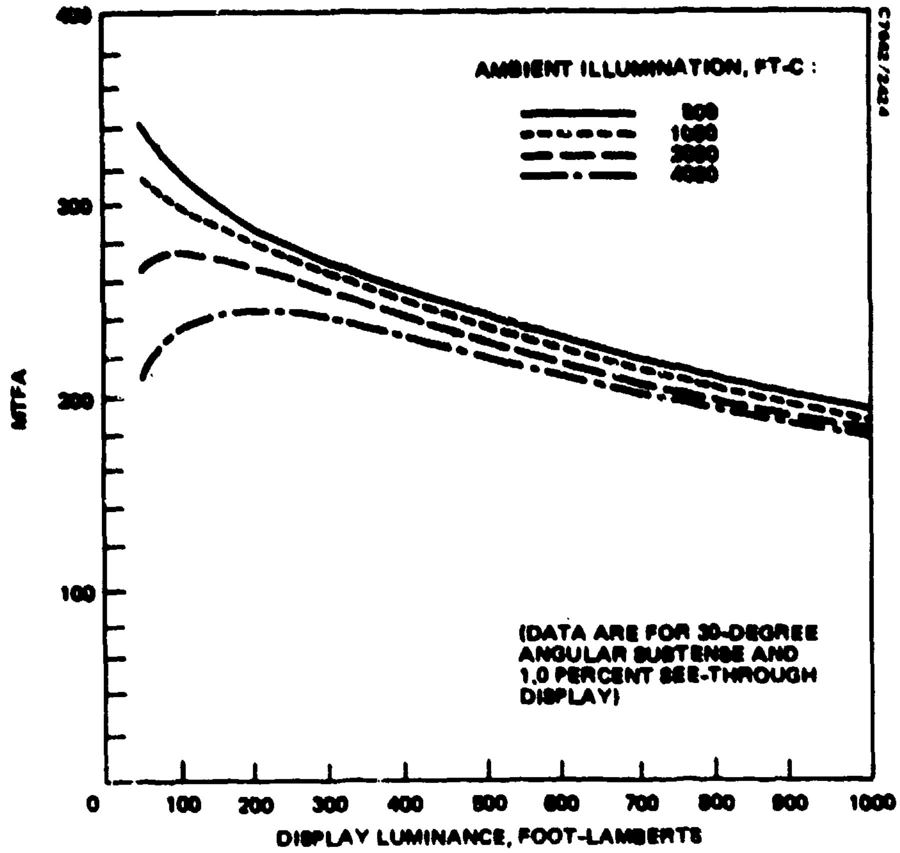


Figure 51. MTFA as a function of display luminance and ambient illumination.

The angular subtense of the dispaly within the range of 15 to 45 degrees had no appreciable effect on MTFA as shown in Figure 52.

Figure 53, 54, and 55 show the number of $\sqrt{2}$ gray shades as display luminance, ambient, illumination, and percent see-through are varied. Increasing ambient illumination and percent see-through reduces the number of gray levels, and increasing display luminance counteracts the combined effects of ambient and see-through to increase gray shades.

The analysis and metrics of image quality considered in the foregoing may be used for evaluating the relative merits of candidate HMDs, but cannot presently be used as absolute measures of system performance. From the results presented, the following trends were observed:

- Ambient illumination levels between 500 and 4000 FTC have a negligible effect on eye limiting resolution of virtual image displays whose brightness is greater than 50 fL.

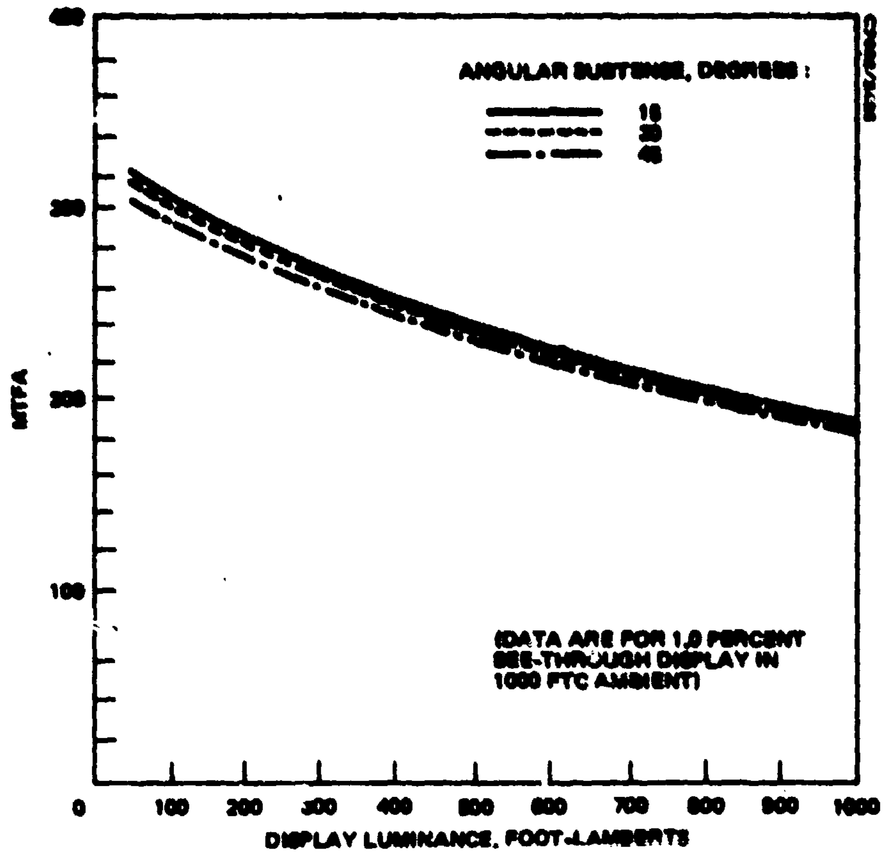


Figure 52. MTFA as a function of display luminance and display angular subtense.

- Image quality of occluded displays is essentially equivalent to see-through displays with transparencies equal to and less than 0.1 percent.
- Eye limiting resolution decreases with increasing display luminance and increases with angular display subtense.
- MTFA improves with decreasing values of the see-through transparency and degrades with increasing ambient. However, displays brighter than 100 fL and with transparencies less than 0.1 percent are unaffected by ambients between 500 and 4000 foot-candles.
- MTFA is not affected by display angular subtenses within the range of 15 to 45 degrees.
- Dynamic range and gray scale rendition are improved with decreasing values of see-through transparency.

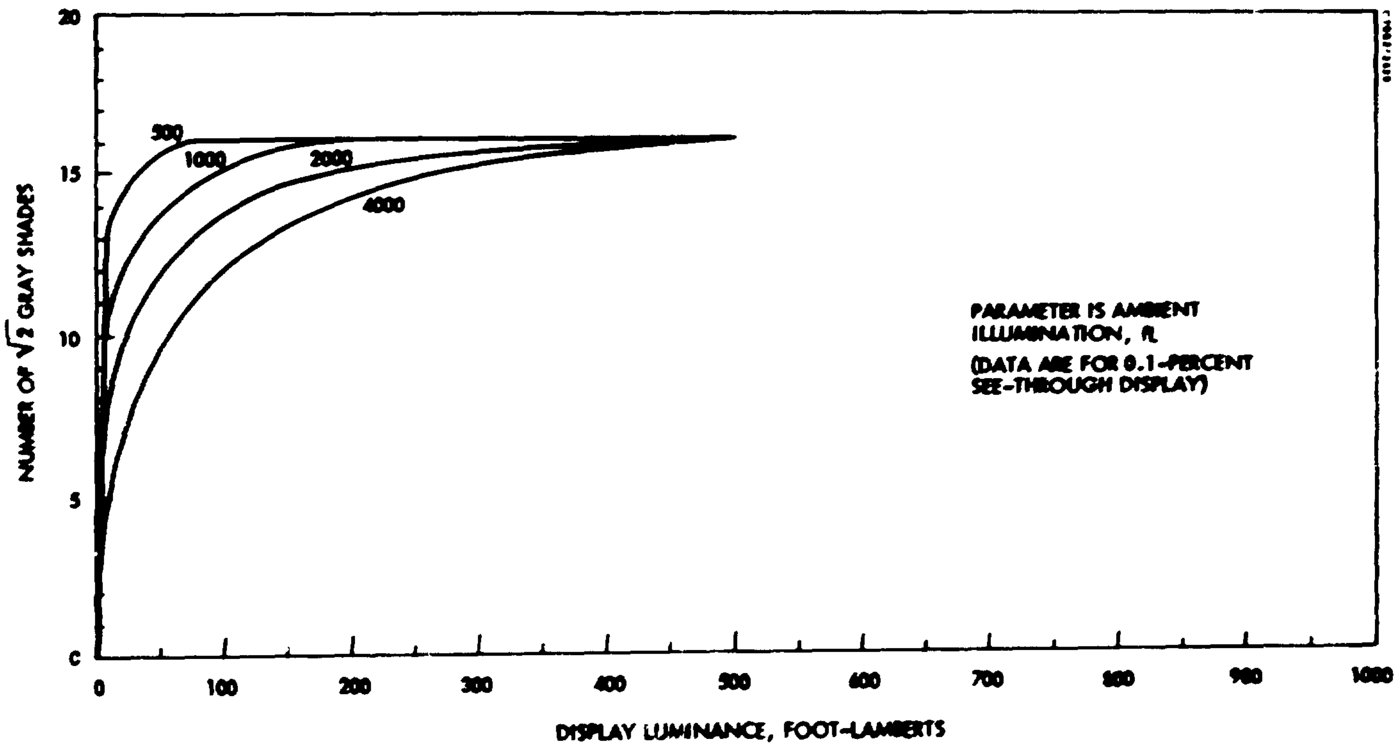


Figure 53. Number of $\sqrt{2}$ gray shades as a function of display luminance and ambient luminance for 0.1-percent transmission see-through display.

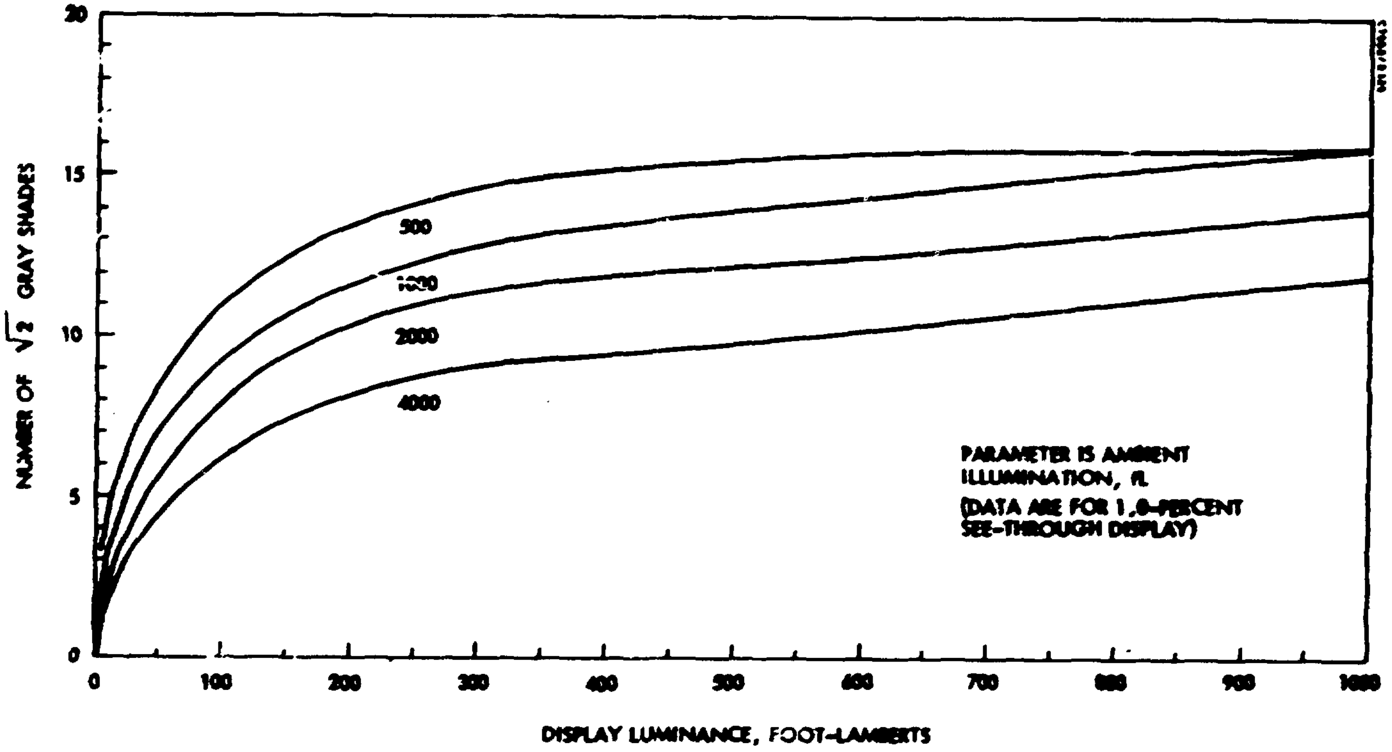


Figure 54. Number of $\sqrt{2}$ gray shades as a function of display luminance and ambient luminance for a 1.0-percent transmission see-through display.

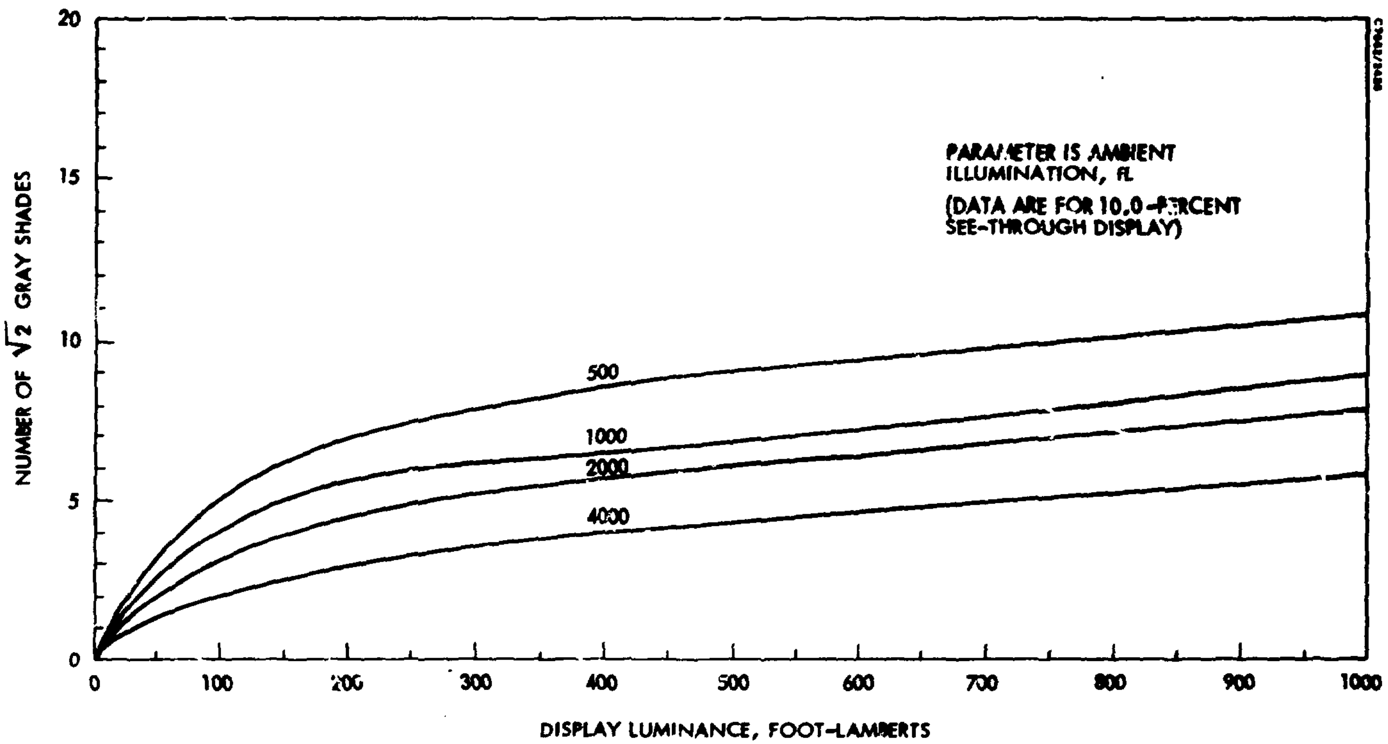


Figure 55. Number of $\sqrt{2}$ gray shades as a function of display luminance and ambient luminance for a 10-percent transmission see-through display.

APPENDIX A

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APPENDIX B

INSTRUCTIONS TO SUBJECTS

INSTRUCTIONS TO SUBJECTS FOR SCREENING STUDY OF BINOCULAR RIVALRY IN HELMET-MOUNTED DISPLAYS

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a laboratory research study to determine those image parameters and their range of values which are associated with the control or elimination of binocular rivalry in helmet-mounted displays.

Binocular rivalry is a phenomenon that occurs when different images are simultaneously presented to each eye in such a way that binocular fusion of the two images cannot occur. The phenomenon is manifested either by the two images alternating as the dominant one, or an unstable montage is formed, comprised of elements from each field.

Rivalry is obviated when one of the two images so completely dominates the other that alternation of the two fields does not occur. This is a desirable situation from the point of view of HMD design if the conditions under which one or the other field will dominate can be identified and placed under the control of the observer. Essentially, this is one of the primary goals of this study.

Unlike conventional displays, the virtual image from a helmet-mounted display (HMD) will characteristically be viewed by one eye, while another image, the ambient scene, will be viewed by the open eye.

The apparatus you will use in this study simulates the HMD situation. An image representing the HMD scene will be projected onto a screen, while another image representing the ambient scene, will be projected onto a second screen. The apparatus is so designed that each eye will view a different projected image.

The ambient scene image will be either a ground scene or a cockpit scene, and each will vary during the study in luminance and accommodation. The HMD scene will vary throughout the study according to combinations of different values of the following parameters: resolution, contrast, field-of-view, eye presentation, color, framing, luminance, accommodation, and percent transparency. The complexity of the area of superimposition of the two images will also be varied.

You will be given two 1-minute test trials on each of eight different combinations of the above conditions. Your task will be to evaluate the degree to which the HMD scene or the ambient scene is visible, by moving a linear control lever from full back, to indicate 100 percent ambient scene visibility, through full forward, to indicate 100 percent HMD scene visibility. Visibility, as used here, is difficult to define objectively, since it is actually a subjective experience of the rivalry situation. Its meaning will become more apparent during the training trials.

The control lever is spring mounted and comes to rest at the middle of its stroke. This control lever position would indicate that both images are partially, but equally visible, i.e., 50 percent visibility for each image. If, when you begin each trial, both images are not equally visible, move the control lever to a position that expresses your judgment of which image is most visible and to what degree. For example, if you see 75 percent of the HMD image and 25 percent of the ambient image, move the control lever forward to a point about half-way between the middle, or 50 percent position, and the full-forward, or 100 percent position. Should you see 75 percent of the ambient scene and 25 percent of the HMD scene, move the control lever backward to a point about halfway between the middle and full-back positions. If you see 100 percent of either image, move the control lever as far as it will go in the appropriate direction.

Some of the HMD images are of very poor quality. Remember, you are not being asked to judge image quality, you are being asked to judge visibility, i.e., how much of the image you can see, regardless of its quality.

The spring tension on the control lever will provide kinesthetic feedback of the approximate position of the control lever. You will be given training trials to become familiar with the binocular rivalry phenomenon and to gain experience with the control lever.

After every two 1-minute test trials, study conditions must be changed for the following trial. Because of their number, changing of conditions may take 5 to 8 minutes.

The procedure for test trials is as follows. After being seated at the apparatus, place your chin in the chin rest and look at the images presented on the screens. The experimenter will point out the object in the HMD image which you are to evaluate in terms of percent visibility. When you are satisfied that you understand which part of the image to attend to, close your eyes and tell the experimenter that you are ready. The experimenter will then say, "One, two, three, start." When you hear the word "start", open your eyes and begin to move the control lever in response to your visual impressions of the image. After 1-minute has elapsed, the experimenter will say, "Stop", indicating the completion of that trial. After two 1-minute trials at each condition, you will be asked to take a different seat so that the experimenter can adjust the equipment for the next trial. When all adjustments have been made, you will again be seated at the test apparatus. This procedure will be repeated for 16 trials (two trials for each of eight conditions).

INSTRUCTIONS TO SUBJECTS FOR PARAMETRIC STUDY OF BINOCULAR RIVALRY IN HELMET-MOUNTED DISPLAYS

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a laboratory research study to determine those image parameters and their range of values which are associated with the control or elimination of binocular rivalry in helmet-mounted displays.

Binocular rivalry is a phenomenon that occurs when different images are simultaneously presented to each eye in such a way that binocular fusion of the two images cannot occur. The phenomenon is manifested either by the two images alternating as the dominant one, or an unstable montage is formed, comprised of elements from each field.

Rivalry is obviated when one of the two images so completely dominates the other that alternation of the two fields does not occur. This is a desirable situation from the point of view of HMD design if the conditions under which one or the other field will dominate can be identified and placed under the control of the observer. Essentially, this is one of the primary goals of this study.

Unlike conventional displays, the virtual image from a helmet-mounted display (HMD) will characteristically be viewed by one eye, while another image, the ambient scene, will be viewed by the open eye.

The apparatus you will use in this study simulates the HMD situation. An image representing the HMD scene will be projected onto a screen, while another image representing the ambient scene, will be projected onto a second screen. The apparatus is so designed that each eye will view a different projected image.

The ambient scene image will be a ground scene and will vary during the study in luminance. The HMD scene will vary throughout the study according to combinations of different values of the following parameters: resolution, contrast, field-of-view, and luminance.

You will be given two 1-minute test trials on each of nine different combinations of the above conditions. Your task will be to evaluate the degree to which the HMD scene or the ambient scene is visible, by moving a linear control lever from full back, to indicate 100 percent ambient scene visibility, through full forward, to indicate 100 percent HMD scene visibility. Visibility, as used here, is difficult to define objectively since it is actually a subjective experience of the rivalry situation. Its meaning will become more apparent during the training trials.

The control lever is spring mounted and comes to rest at the middle of its stroke. This control lever position would indicate that both images are partially, but equally visible, i.e., 50 percent visibility for each image. If, when you begin each trial, both images are not equally visible, move the control lever to a position that expresses your judgment of which image is most visible and to what degree. For example, if you see 75 percent of the HMD image and 25 percent of the ambient image, move the control lever forward to a point about half-way between the middle, or 50 percent position, and the full-forward, or 100 percent position. Should you see 75 percent of the ambient scene and 25 percent of the HMD scene, move the control lever backward to a point about halfway between the middle and full-back positions. If you see 100 percent of either image, move the control lever as far as it will go in the appropriate direction.

Some of the HMD images are of poor quality. Remember, you are not being asked to judge image quality, you are being asked to judge visibility, i.e., how much of the image you can see, regardless of its quality.

The spring tension on the control lever will provide kinesthetic feedback of the approximate position of the control lever. You will be given training trials to become familiar with the binocular rivalry phenomenon and to gain experience with the control lever.

After every two 1-minute test trials, study conditions must be changed for the following trial. Because of their number, changing of conditions may take 3 to 4 minutes.

The procedure for test trials is as follows. After being seated at the apparatus, place your chin in the chin rest and look at the images presented on the screens. The experimenter will point out the object in the HMD image which you are to evaluate in terms of percent visibility. When you are satisfied that you understand which part of the image to attend to, close your eyes and tell the experimenter that you are ready. The experimenter will then say, "One, two, three, start." When you hear the word "start", open your eyes and begin to move the control lever in response to your visual impressions of the image. After 1-minute has elapsed, the experimenter will say, "Stop", indicating the completion of that trial. After two 1-minute trials at each condition, you will be asked to take a different seat so that the experimenter can adjust the equipment for the next trial. When all adjustments have been made, you will again be seated at the test apparatus. This procedure will be repeated for 18 trials.

INSTRUCTIONS TO SUBJECTS FOR VALIDATION STUDY OF BINOCULAR RIVALRY IN HELMET-MOUNTED DISPLAYS

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a laboratory research study of operator performance on target recognition and tracking tasks using helmet-mounted displays (HMDs). With an HMD, the display is viewed with only one eye, while the other eye views everything other than the HMD. This situation produces binocular rivalry, since each eye is viewing a different image. Binocular rivalry is a psychological phenomenon wherein the viewer perceives either an unstable montage comprised of parts of each image, or an alternation of the two images. The relative percentage from each field which is perceived in the montage, or the rate of alternation of the two images depends upon the "contour strength" of each image. Contour strength is a function of such parameters as resolution, contrast, image complexity, and luminance. When the contour strength of one image is greater than the other, that image will predominate in the alternation cycle. If the relative difference is very large, one image may totally dominate the other, i.e., no alternation will occur and only the dominant image will be perceived.

It is expected that in a binocular rivalry situation, such as occurs with an HMD, operator tasks requiring information retrieval from the image presented to either eye will be degraded as a function of the contour strength of the image presented to the contralateral eye.

In this study you will be asked to perform target recognition and tracking tasks under conditions in which the contour strength of each image is varied relative to that of the opposing image. Contour strength of the non-HMD visual field will be varied by manipulation of image luminance. Contour strength of the HMD image will be varied by manipulating resolution, contrast, and luminance. There will be nine different conditions under which the two tasks will be performed.

The test procedure will be as follows. After being seated at the HMD simulation apparatus the equipment will be adjusted to ensure that the HMD image and the tracking task dial are visible. The HMD will be presented to your left eye and the dial to your right eye. The experimenter will then show you sketches of a target which you are to recognize on the HMD. When you are ready to begin, the experimenter will ask you to close your eyes and the target image will be placed on the HMD projector. The experimenter will then say, "One, two, three, start." When you hear the word "start," open your eyes and immediately search the HMD scene for the target. The experimenter will start a digital readout timer simultaneously with his command "Start," to record your response time. When you recognize the target, so indicate by saying "There," and simultaneously press the response button to stop the timer. After you have recognized it, you will be asked to point to the target on the screen so the experimenter can determine whether you correctly recognized the target.

The tracking task will immediately follow the target recognition task under the same experimental conditions. For this task, you are to attempt to keep the pointer on the cockpit dial at the null or center position. The pointer will move across the dial in response to the input of a pure sine wave. Your task is to keep the pointer centered using a tracking control lever. Again, you will begin with your eyes closed and open them and begin tracking at the experimenter's command "Start." The tracking task duration will be 1 minute. Your tracking error will be measured by a computer.

The completion of the tracking task marks the end of one trial. The above procedure will be followed for nine trials. You will be given training trials to familiarize yourself with the procedures and the test equipment. Do not attempt, during any of the trials, to see either image by closing the opposite eye. Both eyes must be kept open for all training and test trials.

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